USING EMG SPECTRAL ANALYSIS AS A QUANTITATIVE MEASURE OF MOTOR UNIT RECRUITMENT TO EVALUATE STROKE MOTOR RECOVERY

By

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After stroke, motor function is often reestablished abnormally in the paretic limb, causing difficulty in daily tasks. The two primary purposes of this study were to apply spectral properties, namely mean peak frequency shifts and changes in average power over four frequency bins from surface EMG recordings, to describe motor unit recruitment in the muscles of the wrist/finger extensors, and to correlate functional improvements, namely increased force production, to improved motor unit recruitment patterns.

Using data collected from 2002 through 2006 from two separate training protocols, twenty five chronic patients were selected for analysis. The first protocol consisted of a pretest, a 2 week (4 sessions) coupled bilateral training and active EMG-neuromuscular stimulation protocol, and a posttest. The second group (Weighted) underwent a pretest and posttest identical to previous group (Coupled), but participated in a coupled bilateral training and active EMG-neuromuscular stimulation with an added weight on the affected hand.

Separate analyses were conducted on the three dependent measures (average power, mean peak frequency, and mean force) using a four-way mixed ANOVA. Significant results were revealed in the low gamma power band, in addition to mean peak frequency and mean force ($p < 0.05$). In the low gamma band, the unaffected limb in the unimanual condition during the posttest exhibited significantly higher power than every other combination of condition, limb, and session. Moreover, the unaffected limb showed a significantly higher mean peak frequency than the affected limb. In addition, the unaffected limb in the coupled group showed higher mean peak frequency than the affected limb in the same group. The affected limb in the coupled group also displayed a lower mean peak frequency than the unaffected limb in the weighted group. Analysis of the force data revealed higher force when moving unimanually compared to moving bimanually. As expected, the affected limb produced a lower amount of force compared to the unaffected limb in both unimanual and bimanual conditions.

Findings support previous research stating that the unaffected limb exhibits higher power than the affected limb, indicating that the unimpaired limb is able to harness larger motor neurons in its recruitment strategy, thus leading to larger force production. Each subject exhibited improvement in at least one category, number of blocks moved, increased mean peak frequency, a change in power in the 30-55 Hz bands, or amount of force produced. However, no single uniform characteristic of motor improvement was shown by each stroke subject. The current findings indicate that the training is affecting the stroke patients positively and merits further research

INTRODUCTION AND REVIEW OF LITERATURE

Normal Motor Unit Recruitment

The principle of motor unit recruitment states that motor units, consisting of the motor neuron and the muscle fibers it innervates, are progressively activated with increasing strength of voluntary muscle contraction (Milner-Brown *et al*., 1973). The central nervous system increases the strength of muscle contraction by increasing the number of active motor units or increasing the firing rate of individual motor units. Both of these mechanisms occur concurrently, though the recruitment of more motor units takes precedence over an increase in firing rate until nearly all motor units are recruited. Once this level is reached, motor units are driven to fire in their secondary range to rates greater than 50 Hz (Petajan, 1991).

Motor units are recruited according to the order of their size. The first motor units to fire are small in size, weak in force generation, and resistant to fatigue. Progressively larger motor units with greater force production capabilities are recruited with increasing strength of muscle contraction (Henneman *et al.,* 1965). As large motor units are activated, it is important to note that the smaller units are still firing, although the large motor units assume primary responsibility for maximum force production. This sequential recruitment order is known as the Henneman size principle and it results in a smooth increase in muscle strength. Through their feline research paradigm, Henneman and colleagues discovered that axon diameter, conduction velocity, and cell size all increase with increased muscle contraction (Henneman *et al*., 1965). The three main types of motor units include Type I fibers, described as slow twitch, small, fatigue-resistant units which generate the least force and have the slowest contraction time, Type IIa units that are fast-twitch, larger, fatigue-resistant units able to generate greater forces and faster contraction times, and Type IIx units, known as the largest, fast-twitch, easily-fatigable units capable of the greatest force production and fastest contraction time. Motor unit recruitment sequences begin with Type I motor units and then sequentially advance to Type IIa and finally Type IIx units for high force production. The late recruited Type II fibers have larger diameters and thus generate higher motor unit action potentials (MUAPs) than the smaller Type I fibers. This size principle is used in electromyography (EMG) studies designed to analyze motor unit recruitment patterns by using the amplitude of the MUAP to define the size of a specific motor unit (Ertas *et al.,* 1995).

A confluence of MUAPs traveling along the sarcolemmas of the muscle fibers results in a muscle contraction. Myoelectric signals are formed on the basis of the interference pattern among these MUAPs and are detected using EMG. The conductance and resistance of the sarcolemma differ between fast- and slow-twitch fibers (Luff & Atwood, 1972) and therefore, researchers postulate that different types of muscle fibers generate different MUAPs. Myoelectric signals provide information about the form of the MUAPs and are able to offer insight into the electrophysiology of the active muscle. Signals measured using intramuscular EMG in animals have shown that faster motor units generate higher frequencies in their power spectra (Wakeling & Rozitis, 2004). However, evidence from surface EMG in humans has remained elusive on this topic. Recent advances in EMG signal decomposition including wavelet techniques, Fourier

Transform methods, and simulations that accurately mimic human muscle behavior have provided additional information not previously known, such as motor unit recruitment, muscle fatigue factors, and biomechanical adaptations (Karlsson *et al.,* 2000). For example, when faster motor units are active, increases in mean and/or median myoelectric frequency are observed in the EMG signal, thus suggesting that there is an inherent property of the muscle fiber that can be distinguished within EMG signals (Farina *et al.,* 2002).

Recruitment Following Neurological Insult

After a motor neuron injury such as a stroke, the relationship between motoneuron size and the number and size of the muscle fibers it innervates is usually lost or damaged. Reorganization of this relationship at motor endplates occurs over time through axon branching and neuromuscular activity (Nudo, 1999). This reorganization, known as neuroplasticity, occurs as the nervous system attempts to repair damaged motor neurons. Therefore, there must be persistent functional changes evident in the brain, and consequently in motor unit activity, to represent this new organization. Using spectral analysis to analyze MUAPs post-stroke and after bimanual coordination training will offer insight into abnormal motor unit recruitment strategies post-stroke and aid in the explanation of new strategies employed after a specific training protocol.

After a cerebrovascular accident (CVA), such as stroke, motor unit recruitment is altered because of interrupted descending pathways as well as structural changes in the muscle (Mazevet *et al.,* 2003). Brain damage secondary to stroke results in corticospinal and supraspinal motor pathway disruption and possibly leads to synaptic degeneration at the segmental level (McComas *et al.,* 1973). This loss of neural signaling at the segmental level causes motor neuron loss and altered force control mechanisms. Muscle impairment following stroke can result from several sources including loss of motor units because of Wallerian degeneration (McComas *et al.,* 1971). As a result of the Wallerian degeneration, all of the muscles fibers previously innervated by the axon are denervated and therefore, fewer motor units are available for muscle activation. Altered properties of the motor unit affect recruitment through altered recruitment order, discharge rate, and/or discharge pattern (Beaumont & Gardiner, 2002). This abnormal motor unit recruitment in turn, impacts the level of impairment post stroke. For instance, in neurologically healthy individuals, once the first recruited muscle unit reaches a firing frequency of 10 Hz, a second unit begins firing to increase muscle force. However, after stroke, this second unit is often missing or damaged and an increase in force can only be achieved by increasing the firing rate of the first motor unit(s). This abnormal recruitment and discharge pattern contributes to the inefficient and undesired movement patterns often observed in stroke patients. Adding to the underlying cause of such inefficient motor patterns is altered motor neuron pool excitability. Altered excitability affects the probability of motor unit activation, and in turn allows expression of unwanted or atypical coordination patterns (Morales *et al.,* 1987).

Low tonic rates are indicative of slow motor units while fast motor units are associated with higher, more phasic tonic rates (Denny-Brown, 1929; Granit *et al.,* 1956). The close matching of motoneurons and muscle properties with respect to firing rates was first described by Kernell and colleagues in muscles of rats and cats (Granit *et al.*, 1963) and later in single motor units of rats (Gardiner and Kernell, 1990) and supports the idea that motor unit recruitment and rate coding both contribute to voluntary force production (Kernell, 1992). That is, the number of motor units that are recruited and the rate of firing of the motoneurons both control force generation of the muscle during voluntary movement. Olson and colleagues successfully reported that a progressive recruitment of motor units occurs when increasing force is required of voluntary movements (Olson *et al.,* 1968). However, impaired voluntary muscle strength results from neurological insult because of a loss of normal motor unit recruitment occurs because of Wallerian degeneration, altered recruitment and discharge patterns, and altered motor neuron pool excitability (Landau & Sahrmann, 2002).

Moreover, drawing consistent conclusions from research involving impaired muscle control in hemiplegic subjects is difficult because of the inconsistencies across studies. For example, a limited number of subjects, a wide variation of lesion duration, and multiple causes of disability are prevalent in stroke motor recovery research. Therefore, the question as to whether the lack of muscular control because of disruption at the supraspinal level, intrinsic changes in the motor neuron pool, or changes in the properties of the muscle itself remains unanswered. However, the literature does agree on the principles that motor unit activation in hemiplegia subjects is non-uniform and motor unit firing rates tend to decrease overall relative to the ipsilesional limb (Rose & McGill, 1998). A consequence of this diminished activation and firing of motor units is a decreased ability to produce voluntary contractions.

Bilateral Training

Promising results have been reported in functional motor improvement post-stroke with bilateral training protocols. Mudie and Matyas (2000) demonstrated enhanced upper limb performance after a three week protocol of bilateral isokinematic therapy (BIT). Bilateral practice with both upper limbs successfully elicited improvements in unilateral performance of the affected limb alone. Motor improvements after bilateral training were greater than those in response to similar unilateral practice or practice sessions that involved the nonparetic limb assisting the paretic limb in various tasks. Significant increases in strength, range of motion, and functional motor ability were reported by Whitall and colleagues (2000) following a six week bilateral training protocol. In addition, Cauraugh and Kim (2002) demonstrated enhanced motor control after EMG-triggered neuromuscular stimulation coupled with bilateral training. These three studies provide support for a bilateral training technique because of the potential effectiveness of the various protocols in improving motor ability of individuals post stroke.

The neural mechanisms and pathways targeted by bilateral training protocols remain uncertain; however, several possibilities have been proposed. One pathway involves an interaction in the affected hemisphere between surviving neurons of ipsilateral pathways and surviving neurons of the crossed corticospinal pathways, the involvement of indirect pathways from the affected hemisphere, and a facilitation of coupling or crosstalk from the unaffected hemisphere to ipsilateral pathways are all possible neural mechanisms responsible for motor improvement exhibited after bilateral training (Mudie & Matyas, 2000). The idea of the coupling principle between arms harnesses existing coupling abilities and encourages recovery of function through bilateral movements. For example, forcing the use of both upper extremeties, as opposed to the paretic arm only, has the potential to yield additional benefits by accessing intact pathways of the unaffected hemisphere and possible coupling mechanisms. Rose and Winstein (2004) reported clear temporal coupling in bimanual conditions and found a facilitation effect in 5 of 11 patients where the paretic limb exhibited a shorter movement time in the bimanual condition. Further, Cunningham and colleagues (2002) reported coupling in bimanual training citing smoother movement of the paretic limb when it was coupled with the nonparetic limb in elbow extension movements. Together these studies support neural coupling as a possible mechanism underlying bilateral training protocols.

Coupled Bilateral Training and EMG-Triggered Stimulation Protocols

In separate studies of EMG-triggered neuromuscular stimulation and bilateral coordination training, motor improvements in hemiparetic subjects were observed (Leonard, 1998; Popovic and Sinkjaer, 2001). These findings are based on accepted motor control theories, including sensorimotor integration and dynamical systems, which complement one another in that the body is viewed as a dynamic system executing movements through an interaction of sensory input and motor actions based on a set of imposed constraints. Both bilateral training and EMG-triggered neuromuscular stimulation essentially activate the same central and peripheral neural mechanisms associated with the pyramidal tract and provide a basis for combining the two protocols. The combination of the two interventions has the potential to accelerate the progress of motor recovery after stroke (Cauraugh & Kim, 2002).

Specifically, Cauraugh and Kim reported an increase in performance of a functional task, decreased reaction times, and increased capability in the sustained force task for the coupled bilateral training and EMG-triggered stimulation group compared to the unilateral and control groups. The coupled intervention group exhibited motor improvement in all three testing categories, exhibiting decreased hemiparesis because of each subject's expanded motor control repertoire (Cauraugh & Kim, 2002; Cauraugh, 2004).

Adding a Load to the Unimpaired Limb

Interlimb coupling is a potentially useful phenomenon in the context of stroke and hemiplegia. It is beneficial to increase the symmetry between the impaired and unimpaired limb through bilateral training in an effort to allow the unimpaired cortex to facilitate the damaged cortex. Interlimb coupling increases with the frequency of the movement, in addition to the torque requirements of the task (Walter and Swinnen, 1990). Therefore, through inertial loading of the unimpaired limb, torque is manipulated and combined with the coupled bilateral training EMG-neuromuscular stimulation protocol for one group in this study.

Spectral Analysis

Raw EMG signals offer valuable information, but in a relatively useless form. Conclusions drawn from raw EMG signals cannot be quantitatively compared between subjects, and therefore most analyses are purely qualitative. Pioneering EMG work began in the 1950’s and has undergone much refinement, especially in the past 20 years due to the advanced processing of computers and other instrumentation. The formal quantitative analysis of MUAP signals is not as cumbersome or time-consuming as it was in the past thanks to recent advances. Among these advances is the ability to use the Fast Fourier Transform (FFT) filter to break the EMG signal into its frequency components which are then graphed as a function of their probability of occurrence and used to determine muscle activation and fatigue.

EMG signal analysis in the frequency domain involves parameters describing specific aspects of the frequency spectrum of the signal. The two most common parameters of the power density spectrum used to determine fatigue are mean and median frequency because they are easily applicable and provide useful information about the

EMG signal. If the EMG spectrum has a normal distribution, these two frequencies will be equivalent, but deviation from normality will result in differing values. Spectral shifts in surface EMG recordings are attributed to the type of muscle fibers activated and are therefore used to characterize motor unit recruitment. Investigation into these shifts has been limited to changes in the mean and median frequency of the power spectrum calculated through FFT (Basmajian & DeLuca, 1985).

The amplitude of the surface EMG is related to the recruitment and the discharge rates of the active motor units. Because of this relationship, EMG amplitude is used as an index of the level of activation provided by the spinal cord. Using FFT, the mean and median frequencies of the EMG signal are identified and analyzed. Shifts in the mean or median frequencies should reflect the recruitment of progressively larger and faster motor units based on Henneman's size principle. Stated differently, variation in muscle fiber conduction velocity has been proposed as an index of motor unit recruitment according to the size principle, and therefore should accurately illustrate motor unit recruitment (Farina *et al.,* 2004).

Data obtained from surface EMG techniques may not need to correlate directly with traditional needle EMG data to be of value in the study of nerve and muscle disorders. For instance, the decline in median frequency of the power spectrum with fatigue or increasing force is a measure that has no single correlate in needle EMG analysis. The combination of surface EMG and computerized signal processing has allowed for nerve and muscle studies that had previously only been analyzed using needle EMG technology. Toulouse and colleagues (1992) studied interference patterns in persons with Guillain-Barré syndrome, a disorder characterized by deterioration in the peripheral nervous system, and normal subjects. They found that surface EMG analysis was useful in quantifying observed changes over the recovery period. In addition, Priez *et al.* (2002) used surface EMG spectral analysis to discriminate between normal subjects and those with muscular dystrophy. Further, the technique was successfully applied to quantifying the severity of the disease. The information gathered by needle EMG is invaluable and superior to surface EMG because of the specificity and accuracy of the signals. However, researchers are encouraged to investigate the value of surface EMG analysis and its ability to provide insight into the study of motor unit recruitment and activity (Hogrel, 2005).

The lowest frequency at which motor units are modulated is 2 Hz. This "common drive" is of central origin and has been found in muscles without muscle spindles (DeLuca, 1985). However, it has only been demonstrated during isometric contractions, where the force slowly increases or is constant (Farmer *et al.,* 1993a). Low frequency common drive persists after stroke, and this further supports the hypothesis that the modulation is of central origin (Farmer *et al.,* 1993b). The next phase of modulation in motor unit firing occurs at a frequency of 5-12 Hz. To date, there is no convincing evidence that this activity is directly controlled by the motor cortex, though peaks in this frequency range have been reported in coherence spectra of the magnetoencephalographic signal (MEG) from the motor cortex and EMG activity (Salenius *et al.,* 1997). The next motor unit activity frequencies include beta (15-30 Hz) and low gamma (30-60 Hz) bands which are regulated by the motor cortex (Brown, 2000). Firing frequencies will vary based on the motor units, muscles, and persons. This rate modulation depends on the intensity of descending motor input which is reinforced by additional local and afferent inputs. Therefore, after stroke when conduction in the central nervous system motor pathways is impaired, motor unit firing patterns are altered (Gemperline *et al.* 1995).

Employing spectral analysis of muscle force as an estimator of motor unit activity has shown that the activity spectra tends to shift to higher frequencies with increasing force in normal subjects. Moritani and Muro (1986) reported increases in surface EMG amplitude and mean power frequency with increasing force. They attributed these changes to progressive increases in the motor unit firing frequency of initially recruited motor units as well as newly recruited motor units. Thus, Moritani and Muro concluded that surface EMG spectral analysis can provide a sensitive measure of motor unit activity during force output. In addition to the normal motor unit activity recorded by surface EMG, Homberg *et al.* (1986) selected patients with different motor dysfunctions to illustrate how motor unit activity was reflected in the power spectra. They reported decreased and increased firing rates, as well as abnormal synchronization across the various motor dysfunctions.

Surface EMG has been shown to be a valuable tool in evaluating motor unit activity. Although intracellular EMG technology is able to provide more detail and insight into single motor unit recruitment, surface EMG data offers a significant means to analyze muscle performance and fatigue. With the mathematical advances of spectral analysis, it is now possible to assess EMG signals in their frequency domains and investigate the effects of observed mean and median power shifts. Combining spectral analysis and surface EMG technology is an interesting approach to analyzing motor unit recruitment and, in turn, quantifying motor recovery after a nerve injury such as stroke.

Purpose

There were two primary purposes for this study: (1) to apply spectral properties, namely mean peak frequency shifts and changes in average power over four frequency bins from surface EMG recordings to describe motor unit recruitment in the muscles of the wrist/finger extensors, and (2) to correlate functional improvements, namely increased force production which has been previously reported (Cauraugh & Kim, 2002) in stroke patients after bilateral training, to improved motor unit recruitment patterns. Differences in the motor unit recruitment patterns of stroke subjects before and after participation in a coupled EMG-neuromuscular stimulation and bilateral coordination training protocol were analyzed. Recruitment patterns exhibited during a sustained contraction task were quantified by the mean peak frequency and average power of EMG recordings. Pre and post data were considered, in addition to unimanual (paretic limb moving alone) versus bimanual (paretic and nonparetic limb moving together) testing conditions.

Hypotheses

After participating in a motor recovery training protocol, force production of the paretic limb is expected to increase. Several mechanisms may be responsible for this increased force production. More specifically, increased force production occurs because of either faster motor neuron firing rates, as measured by mean peak frequency, or recruitment of larger, stronger motor neurons, quantified by average power. Overall, an increase in mean peak frequency is expected in the posttest, which would indicate that subjects are able to fire motor units at a faster rate than was possible before the coupled protocol training. The increase in mean peak frequency is predicted to be greater in the weighted group compared to the coupled group because of the increased torque demands.

In the range of 1-3 Hz, stroke patients should exhibit similar average power pre- and post-training because this modulation has been reported to be preserved after stroke. If frequencies in this lower band are preserved after infarct, then it is likely that they are not controlled by the motor cortex and therefore possibly controlled at a sub-cortical level. There is no convincing evidence for motor cortex control of the next frequency band, 5-12 Hz, though peaks driven by the motor cortex have been reported. Hence, average power of the paretic and nonparetic limbs should mirror each other closely and there will be no significant differences between pre and posttests. In the next two bands, beta (15-30 Hz) and low gamma (30-60 Hz), the paretic limb will exhibit a significantly lower average power compared to the nonparetic limb. This modulation is controlled primarily by the motor cortex which has been damaged by the stroke and therefore, unable to elicit normal control over voluntary movements. The beta and low gamma bands are important in higher aspects of motor control. After motor unit injury such as stroke, there is an inability to shift to these higher frequencies and persons remain “locked” in a low frequency mode (Myers *et al.,* 2004). Bilateral training protocols aim to facilitate crosstalk between the paretic and nonparetic limbs in an effort to increase the functional ability of the paretic limb. Therefore, after two weeks (4 days) of bilateral coordination training, motor unit recruitment in the paretic limb will improve in the beta and low gamma bands. More specifically, it is hypothesized that the average power in the beta and low gamma bands of the paretic limb will increase post-training in both the unilateral and bilateral testing conditions with a larger increase in the bimanual condition compared to the unimanual condition. A larger increase in average power in the beta and low gamma bands for the bimanual condition will be the result of a facilitation effect from the nonparetic hemisphere. A larger increase in power is also expected to be shown in the beta and low gamma bands by the weighted group. The heightened torque demands of the weighted group will harness greater interlimb coupling and result in higher average power in the beta and low gamma bands. Post-training, the paretic limb will be able to recruit larger motor units and fire at an increased frequency which has the potential to lead to greater force production.

METHOD

Subjects

Chronic stroke subjects (N=15; 10 Left CVA, 5 Right CVA) were selected from two coupled EMG-neuromuscular stimulation and bilateral training protocols from 2002-2006. The number of participants was increased from 15 to 25 (N=25; 18 Left CVA, 7 Right CVA) because of an abundance of data, which also increases the power of the results. Volunteer participants had a stroke at least 1 year ago and displayed mild to moderate upper extremity chronic hemiparesis. Although participants were selected from two different studies, each subject participated in the same pre and posttests and participated in a coupled bilateral training and active neuromuscular stimulation protocol.

All subjects met six admission criteria: (1) diagnosis of at least 1 CVA and no more than 2 CVAs on the same side of the brain; (2) an upper limit cutoff point of 80% motor recovery, as assessed by rectified EMG activation patterns and sustained force contractions during direct comparison of the impaired and unimpaired limbs; (3) a lower limit cutoff point of 10° of voluntary wrist or finger extension against gravity from a 90° flexed position; (4) absence of other neurological deficits, including a pacemaker; (5) no use of drugs for spasticity; and (6) no enrollment in another motor recovery rehabilitation protocol. Before testing began, subjects read and signed an informed consent form approved by the Institutional Review Board.

Pretest-Posttest Instruments and Procedures

Motor functions of the upper extremity were evaluated with three categories of measurement. The first category was a functional manual dexterity test termed the Box and Block timed manipulation test. For 1 minute, subjects attempted to reach and grasp a 2.54-cm cube, transport it over a short barrier, release the block, and return to the original side for another block. Figure 1-1 shows a subject performing the task (Cauraugh & Kim, 2002).

Figure 2-1. Subject performing the Box and Block test with his impaired right hand.

The other two categories of measurements were laboratory-based chronometric and force generation tasks: (1) simple reaction time for speed of information processing and rapid muscle onset and (2) sustained muscle contractions and force modulation (stability control). Simple reaction time tests and sustained muscle contractions were performed by the paretic limb alone, the nonparetic limb alone, and both limbs together in a randomized order for each subject. The hands and arms were inserted into separate devices so that isometric wrist/finger extension movements were executed against 11.4-kg load cells. For both arms, force and EMG signals were recorded online. EMG activity of the wrist/finger extensor muscles was recorded with surface electrodes (silver–silver chloride electrodes with an epoxy-mounted preamplifier).

Only the surface EMG data collected during the sustained contraction task were analyzed using spectral analysis. This was in an effort to target the motor unit recruitment strategies post-stroke, which are more clearly represented during a sustained contraction task.

Motor Recovery Protocols: Training Procedures

A treatment session started with stretching, and surface electrodes were attached to the extensor communis digitorum and extensor carpi ulnaris muscles of the impaired limb. The electrodes were connected to an Automove (AM 800) EMG Facilitation Stimulator microprocessor, and when a target threshold level of EMG activity was voluntarily achieved, the unit immediately provided a surface neuromuscular electric stimulation (i.e., 1-second ramp up, 5 seconds of biphasic stimulation at 50 Hz, pulse width of 200 μs, 1-second ramp down, and mA range of 16 to 29) that assisted the muscles to execute a full range of motion. The initial threshold was set at 50 μV, and as participants successfully achieved the target threshold level, the microprocessor unit automatically increased the target level slightly higher. If the threshold level was not met, then the unit decreased the threshold level closer to the amount of voluntary activity that the individual could produce. Trials were separated by 25 seconds of rest.

During each day of training, subjects completed three sets of 30 successful EMG-triggered neuromuscular stimulation trials (approximately 1 hour and 30 minutes) according to the motor recovery protocol group assignments (i.e., bilateral or unilateral movements). The 6 hours of training (4 days) were completed during 2 weeks. This procedure was followed by one group (Coupled, N=16), while a second group (Weighted, N=9) underwent the same routine with an additional weight on the unaffected limb. The weight was approximately 100% of the unaffected hand's mass. To accomplish this, subjects wore a nylon glove with pockets sewn to the top and bottom where small metal weights were placed.

EMG Spectral Analysis

Maximum sustained contractions were used to determine motor unit recruitment patterns. EMG signals were recorded at a sampling rate of 1000 Hz from the wrist extensor muscles, including the extensor carpi radialis longus, the extensor carpi ulnaris, and the extensor carpi radialis brevis. Signals were then lowpass filtered with a 55 Hz cutoff to avoid electrical outlet noise at 60 Hz. After cutting the first and last second off of each trial to avoid any inconsistencies during the sustained contraction test, the power spectrum of the EMG signal during 6 seconds of the sustained contraction phase was calculated. The proportion of power in each of four frequency bins 1 to 3 Hz, 5 to 12 Hz, 15 to 30 Hz, and 30 to 55 Hz was calculated. These frequency bins were used because of their established relation with population changes in motor unit activity (Myers *et al.,* 2004), although only signal frequencies below 55 Hz were analyzed to avoid interference due to electrical outlet noise at 60 Hz.

A window of 1,024 data points with a 50% overlap was used in isometric actions to calculate mean power frequency (MPF) and mean force (MF). Using the same FFT, average power for each of the four frequency bands was calculated.

Statistical Design and Analyses

Separate analyses were conducted on the three dependent measures. The average power for each frequency band was analyzed in a four-way mixed design ANOVA. The between-subjects factors were training group (2: coupled, weighted) and limb (2: paretic, nonparetic). The within-subjects factors were session (2: pretest, posttest) and impaired limb testing condition (2: bimanual, unimanual). The same mixed-design was used to analyze both mean power frequency and mean force.

RESULTS

The findings below include all of the experimental treatment data for 25 subjects. All dependent variables were analyzed in a Group × Condition × Limb × Session (2 × 2 × 2 × 2) mixed ANVOA with repeated measures on the last two factors. Subjects were divided into two training groups, weighted and coupled, and performed wrist extension movements in bimanual and unimanual conditions with both affected and unaffected limbs. This process was followed in the pretest as well as the posttest. All statistical tests were conducted with α set at 0.05. When appropriate, mean comparisons were computed with Tukey's HSD follow-up procedure.

Power Band 1 (1-3 Hz) and Power Band 2 (5-12 Hz)

No significant differences between groups or sessions in either power band were exhibited. There were also no significant differences found between the affected and unaffected limb in either the unimanual or bimanual condition in these lower two power bands.

Power Band 3 (15-30 Hz)

No significant main effects were identified for Condition, Limb, or Session. The analysis indicated a trend for a Group × Condition interaction (F (1, 23) = 3.804, $p < 0.07$) exhibited in Figure 3-1. Subjects in the coupled protocol group exhibited higher power in the unimanual condition compared to subjects in the weighted group in both the unimanual and bimanual conditions. In addition, the analyses also revealed a trend for a Group × Limb interaction (F (1, 23) = 3.721, $p < 0.07$) as seen in Figure 3-2.

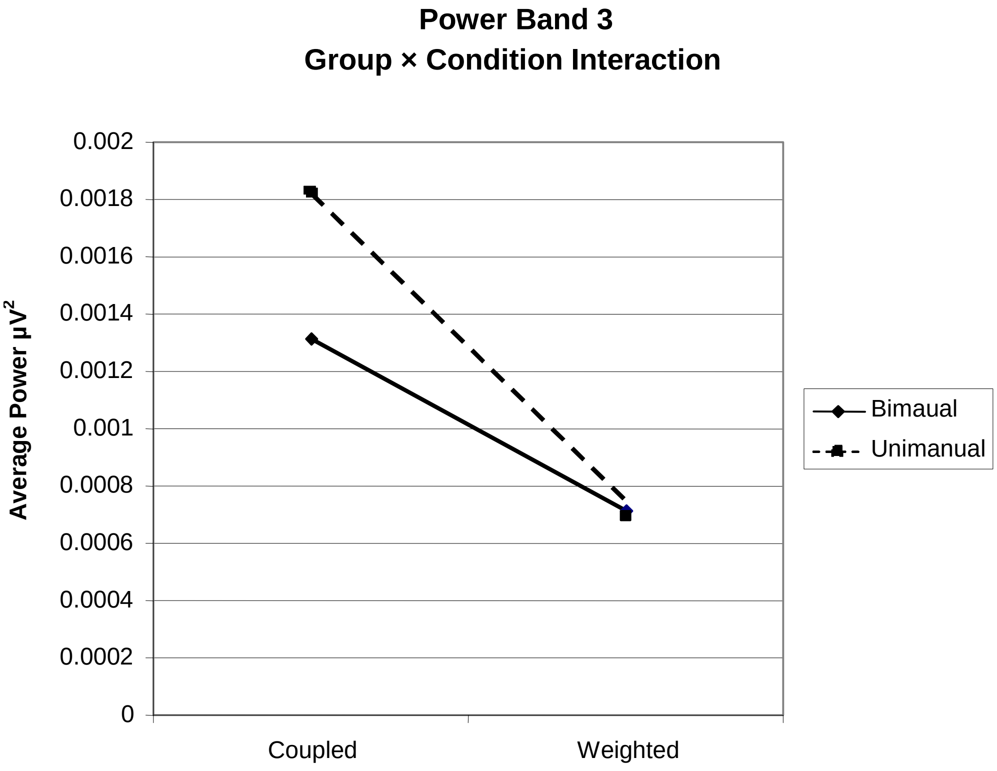

Figure 3-1. Group × condition interaction in power band 3 (15-30 Hz).

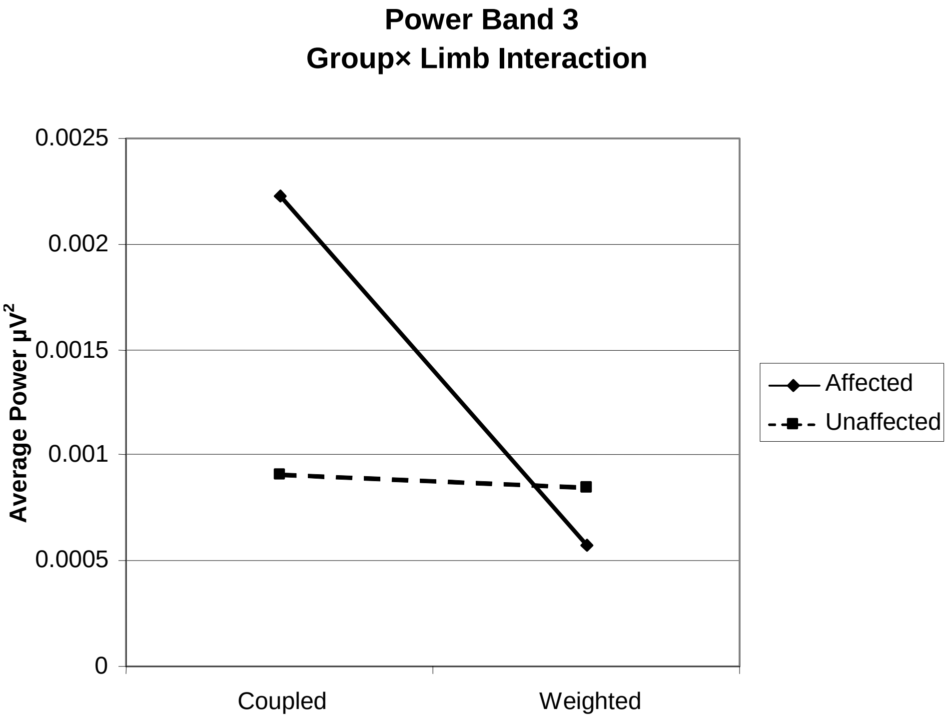

Figure 3-2. Group × limb interaction in power band 3 (15-30 Hz).

The affected limb in the coupled group exhibited a higher power that was statistically different from the unaffected limb in the coupled group as well as both the unaffected and affected limbs in the weighted group. The power of the affected limb in the weighted group was significantly lower than the affected limb in the coupled group in addition to the unaffected limbs in both groups.

Power Band 4 (30-55 Hz)

Analyses indicated a trend for a Limb × Condition interaction (F (1, 23) = 3.616, $p < 0.07$) displayed in Figure 3-3. The unaffected limb in the bimanual condition showed a higher power than the affected limb in both unimanual and bimanual conditions. Further, the mixed ANOVA revealed a significant three-way interaction among Limb × Condition × Session (F (1, 23) = 4.417, $p < 0.05$) shown in Figure 3-4. The unaffected limb in the unimanual condition during the posttest exhibited significantly higher power than every other combination of condition, limb, and session; that is, the unaffected limb in the bimanual condition in the pre and posttest and the affected limb in either the unimanual or bimanual condition in the pre and posttest.

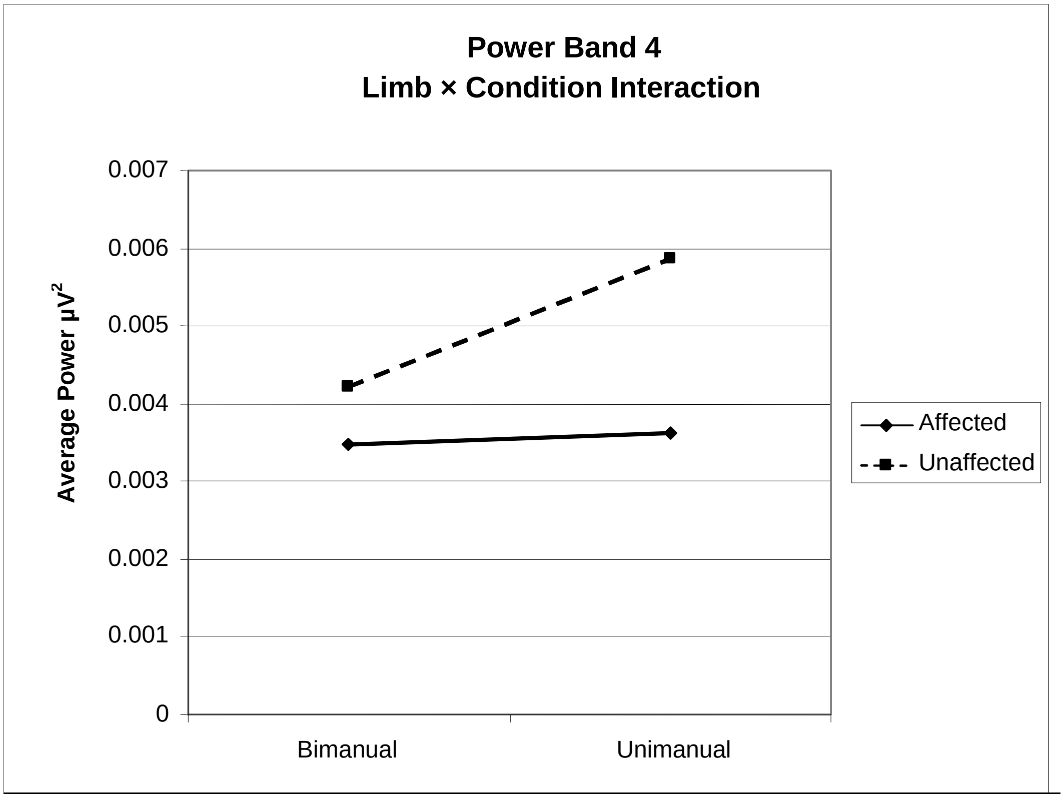

Figure 3-3. Limb × condition interaction in power band 4 (30-55 Hz).

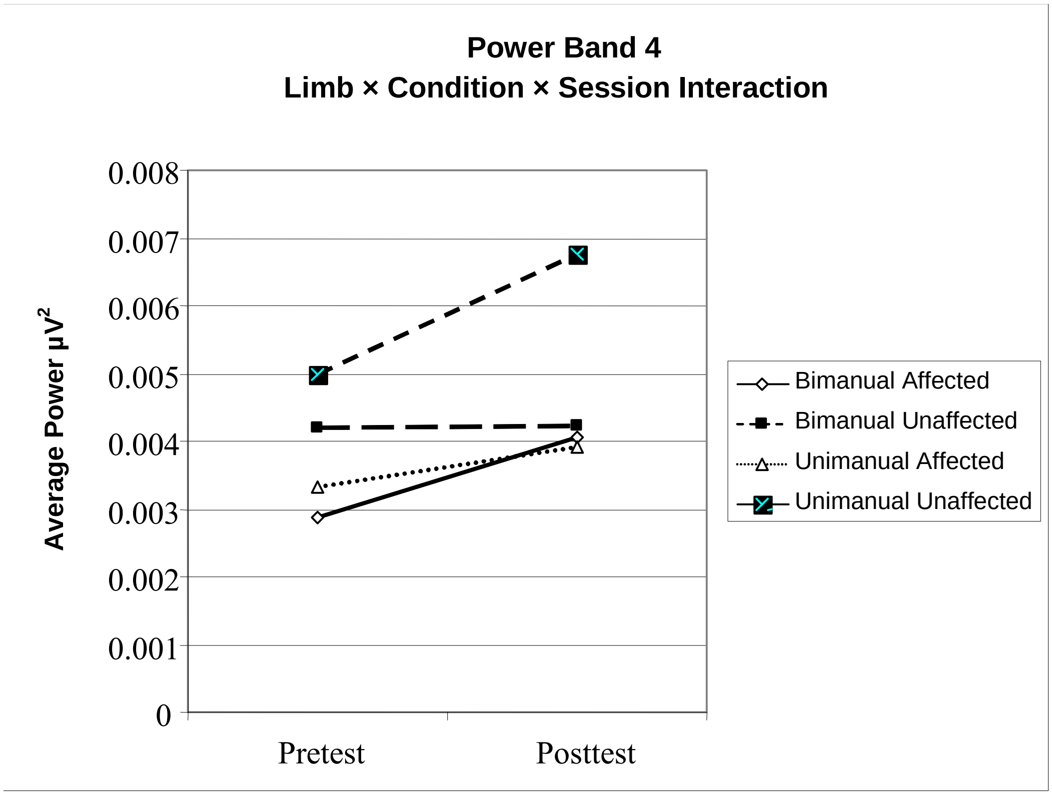

Figure 3-4. Limb × condition × session interaction in power band 4 (30-55 Hz).

Mean Peak Frequency

Analyses from the mixed ANOVA showed a significant main effect for Limb (*F* (1, 23) = 39.987, $p < 0.001$) shown in Figure 3-5. The unaffected limb showed a significantly higher mean peak frequency than the affected limb. Further, a significant Group × Limb interaction (*F* (1, 23) = 5.165, $p < 0.04$) was found (see Figure 3-6). For the coupled group, the unaffected limb performed significantly higher in MPF than the affected limb in the same group. Moreover, the affected limb in the coupled group displayed a significantly lower MPF than the unaffected limb in the weighted group.

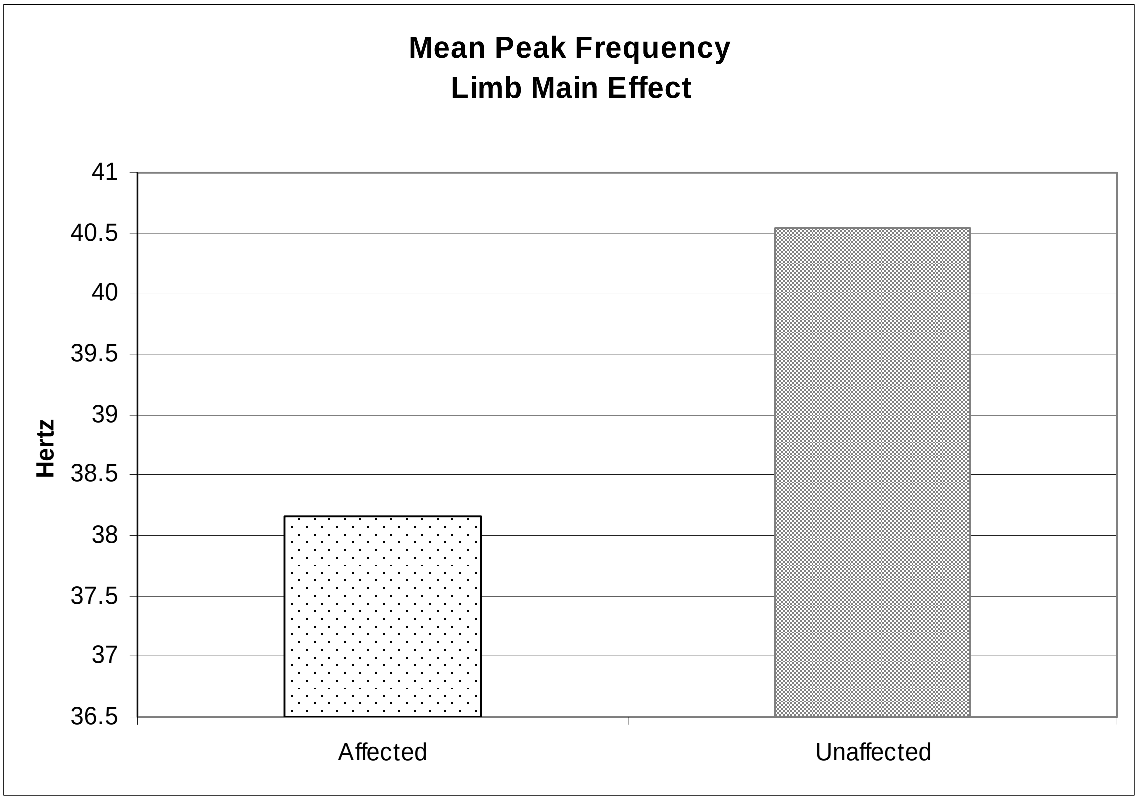

Figure 3-5. Mean peak frequency limb main effect.

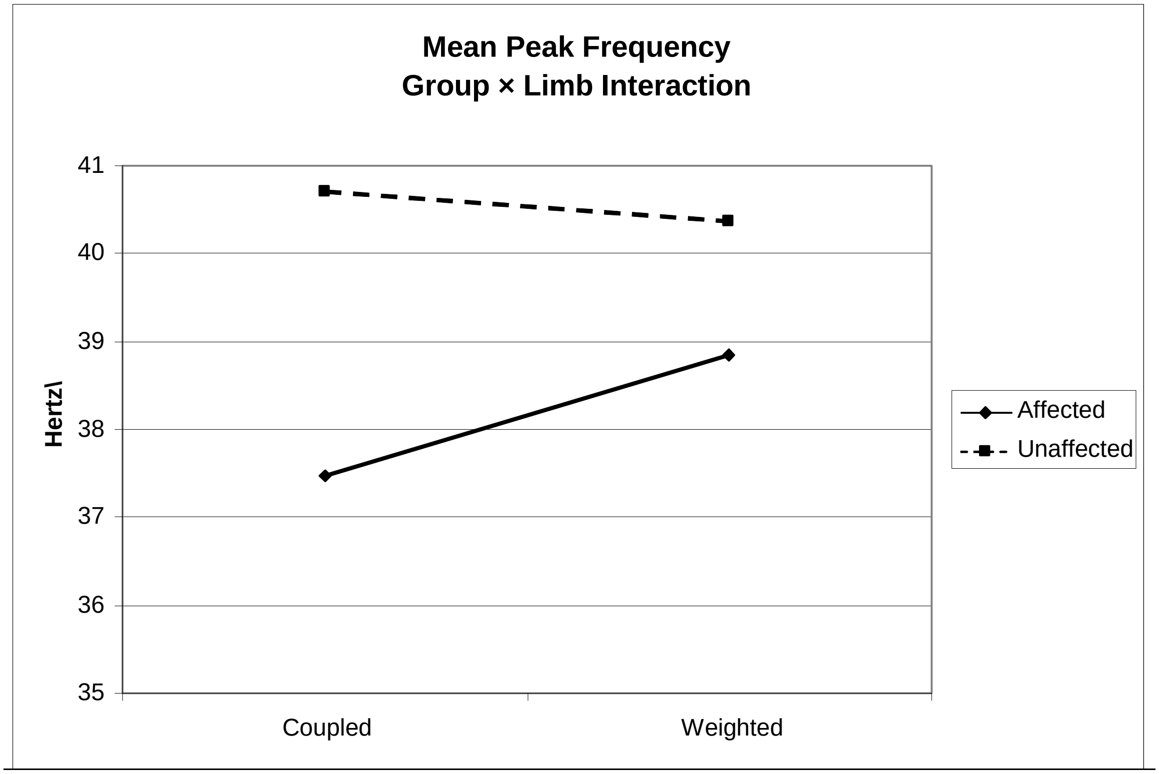

Figure 3-6. Mean peak frequency group × limb interaction.

Force

Analyses of the force data revealed a significant main effect for Condition (*F* (1, 23) = 8.749 $p < 0.01$). Subjects were capable of producing more force unimanually than bimanually. Further, the mixed ANOVA exhibited a significant main effect for Limb (*F* (1, 23) = 66.268, $p < 0.0001$). Comparing the two means indicated that the unaffected limb produced more force than the affected limb. Lastly, a significant Limb × Condition interaction (*F* (1, 23) = 8.708, $p < 0.01$) was found. Follow-up test revealed that the affected limb in the bimanual condition produced a significantly lower amount of force when compared to the unaffected limb in both unimanual and bimanual conditions. The unaffected limb produced significantly less force bimanually than unimanually. Significant main effects and interaction are displayed in Figures 3-7, 3-8, and 3-9 respectively.

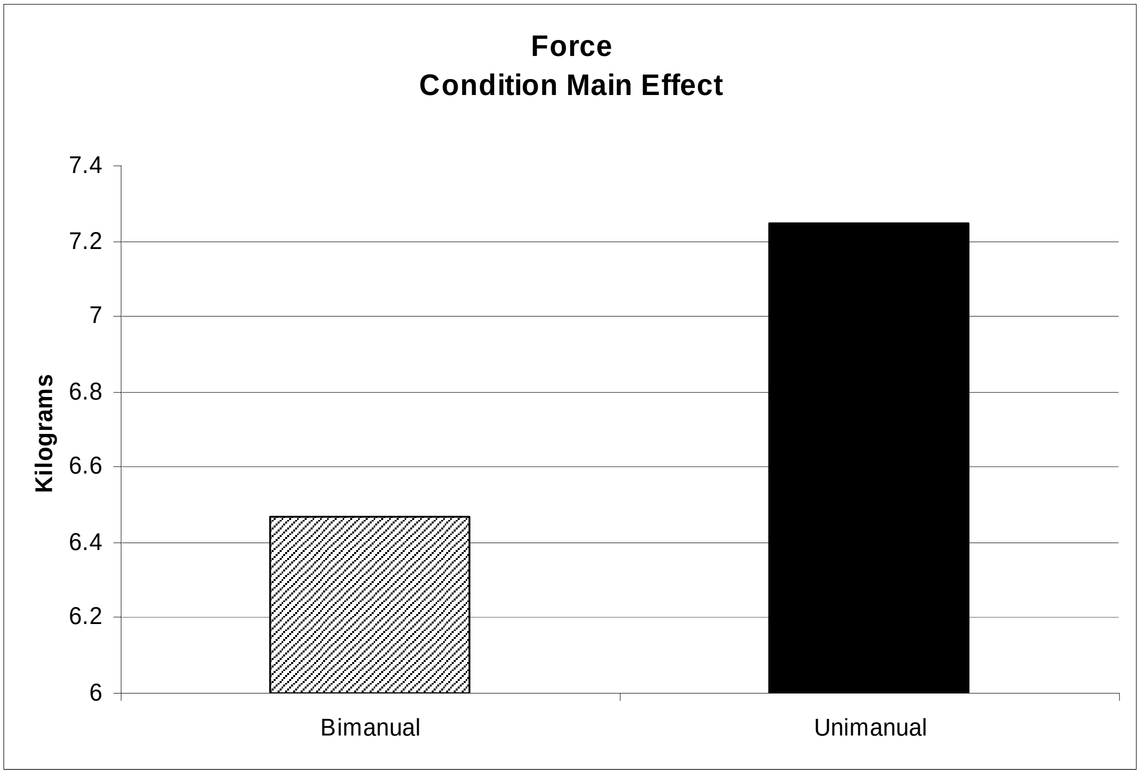

Figure 3-7. Condition main effect.

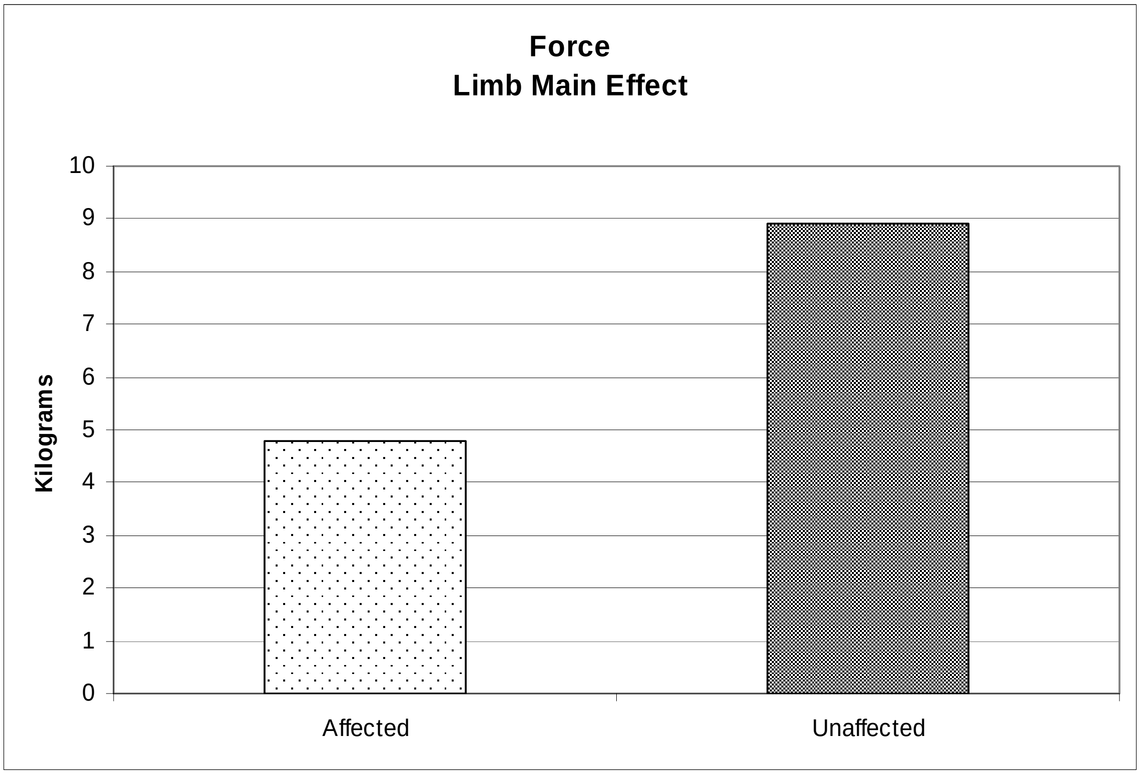

Figure 3-8. Limb main effect.

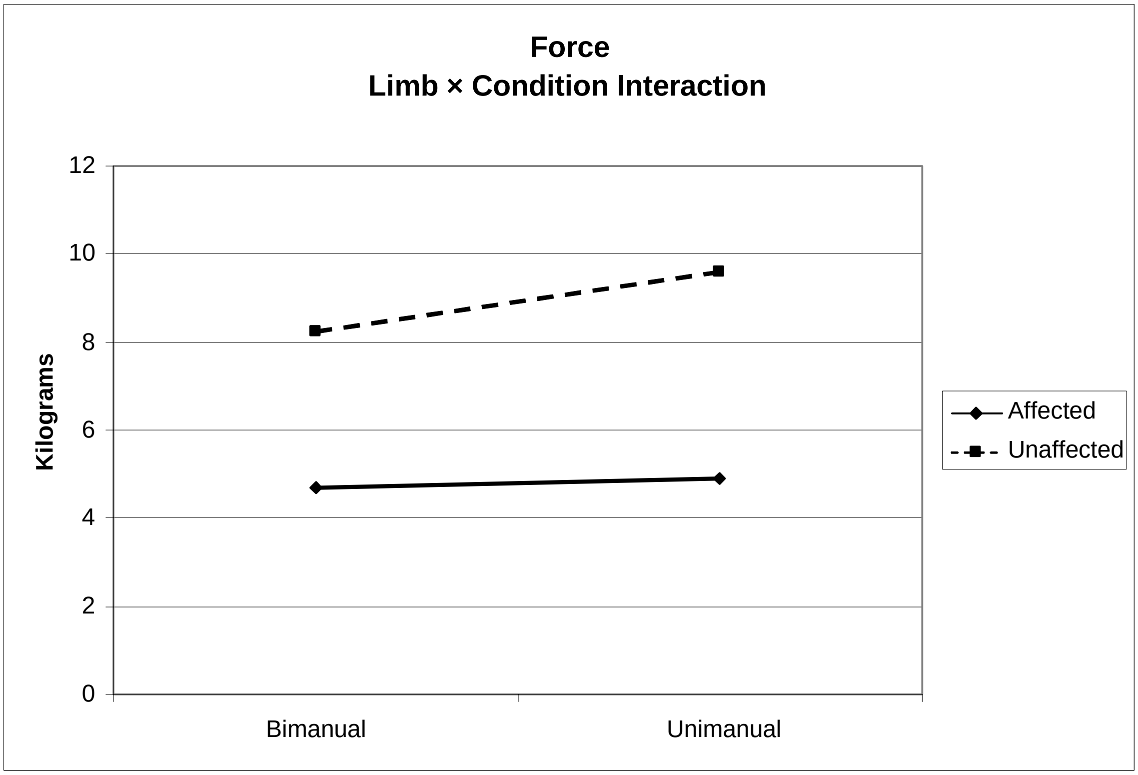

Figure 3-9. Limb × condition interaction.

DISCUSSION

Wrist and finger extension control is one of the most difficult movements to regain after stroke. Given that this control is the basis for many simple, everyday movements such as picking up a cup or turning a doorknob, it is extremely important to understand its rehabilitation and motor recovery. If researchers can identify the physiological basis for regaining motor function in the wrist and fingers, then potentially, stroke therapy could target these specific aspects of motor improvement, making therapy more effective and efficient.

In accordance with the original hypotheses and previous research findings, there were no significant differences between the unaffected and affected limbs in power bands 1 and 2 (1-3 Hz and 5-12 Hz), nor was a training effect found. These results support the idea that the motor cortex does not control movements at low frequencies below 12 Hz and that the firing frequencies in the 1-3 Hz and 5-12 Hz bands remain unchanged post stroke (Myers *et al.,* 2004).

However, increased power was expected after training in the 15-30 Hz and 30-55 Hz power bands as a result of motor cortex rehabilitation. Although the effect for session was not significant, indicating that there were no differences between the pre and posttests, other results were evident. The coupled protocol group exhibited a higher power in the beta band (15-30 Hz) compared to the weighted group when moving unimanually. More specifically, the affected limb in the coupled protocol group showed a higher power than the unaffected limb in the same group as well as the affected and unaffected limbs of the weighted group. These findings do not indicate that the coupled training protocol is definitively more effective than the weighted protocol, but the specific subjects in the coupled group responded to that treatment better. Additional sources of variability include age, movement ability before training, and time since stroke; each may influence the efficacy of the training program. Further, the left hemisphere has been linked to bilateral movement control, so damage to this side may affect training performances (Wyke, 1971). In fact, 18 of 25 subjects in the present study suffered a left CVA, which may explain the absence of the statistically pretest-posttest effect.

For the low gamma band (30-55 Hz), findings revealed a high correspondence with the current hypotheses and previous publications. The unaffected limb exhibited higher power than the affected limb, indicating that the unimpaired limb is able to harness larger motor neurons in its recruitment strategy. The recruitment of larger motor neurons theoretically leads to a larger force production, which is supported by this research. The most force is produced by the unimpaired limb when moving unimanually in the posttest; therefore inferring that the nonparetic hand tends to decrease its force production when coupled with the paretic hand. Research has shown that the nonparetic limb matches the movement time and trajectory of the paretic limb when moving together (Rose & Winstein, 2004). In addition, the current results support previous research (Van Dieen *et al.,* 2003) in that the nonparetic limb attempted to match the paretic limb in force production. Although the affected limb did not exhibit a significant change after the coupled bimanual training protocol, in Figure 3-4, a trend for increased power in the low gamma band exists for the affected limb in the bimanual and unimanual conditions, though a steeper slope is exhibited in the bimanual condition. According to the hypotheses, the affected limb was expected to display an increase in power with a larger increase in the bimanual condition. Though Tukey's HSD post-hoc analyses did not reveal a significant increase, a trend for increased power in the low gamma band in the affected limb is evident. This trend for increased in power in the low gamma band translates into the ability to recruit larger motor neurons and therefore the potential to produce larger amounts of force.

In an effort to explain the results revealed in the four power bands from 1-55 Hz, the entire continuous power spectrum was examined (personal communication, J. Garland, March 31, 2006). Instead of averaging power for each subject across a specific power band, the continuous power spectrum may reveal phenomenon not evident in averaging. After examining each subject's power spectrum, results were inconclusive. There were no trends for an increase or decrease in power in either limb. Subjects showed increases in both limbs (Figures 4-1 and 4-2), decreases in both limbs (Figures 4-3 and 4-4), and increases in one limb coupled with a decrease in the opposite limb (Figure 4-5 and 4-6). Although each subject's power spectrum displays a lower power in the affected limb compared to the unaffected limb in the pretest, each subject responded differently to the training which is clearly supported by the various power spectrum results displayed in Figures 4-1, 4-2, 4-3, 4-4, 4-5, and 4-6.

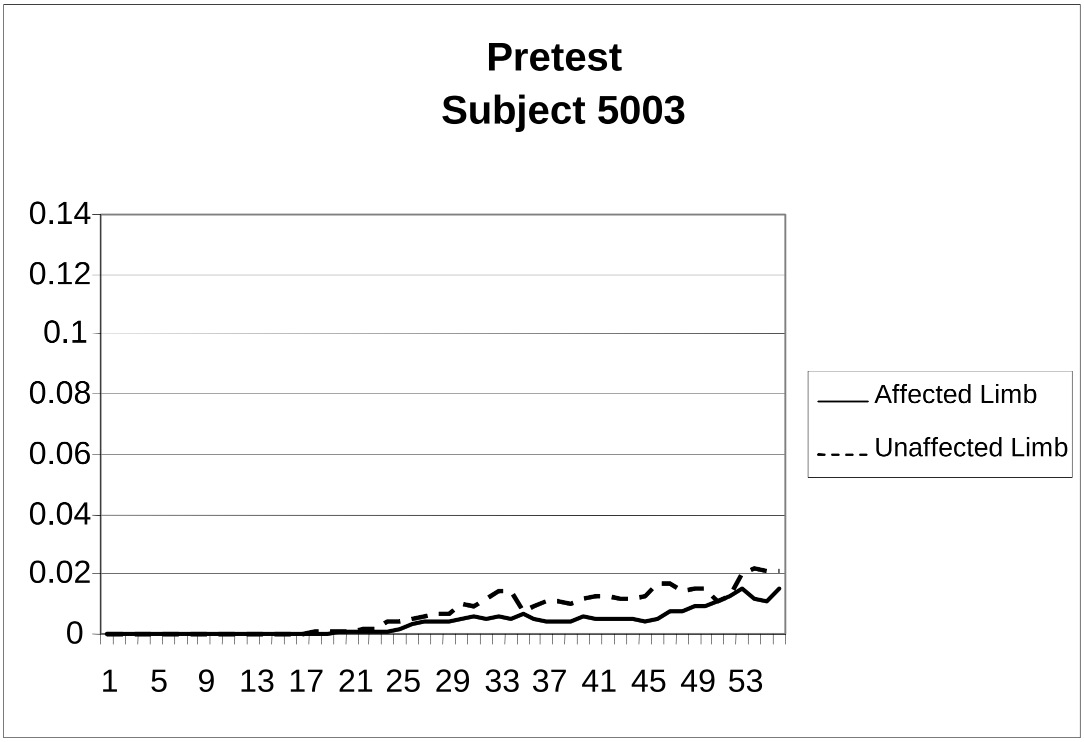

Figure 4-1. Power spectrum. Frequency (Hz) on x-axis. Power (µV2) on y-axis.

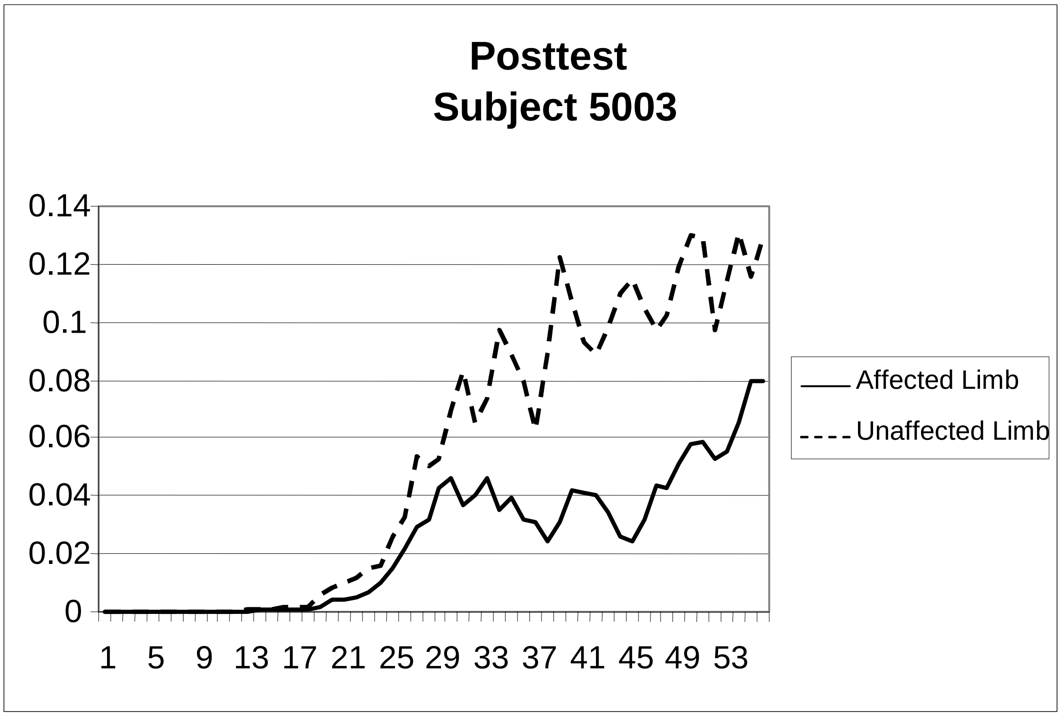

Figure 4-2. Power spectrum. Frequency (Hz) on x-axis. Power (µV2) on y-axis.

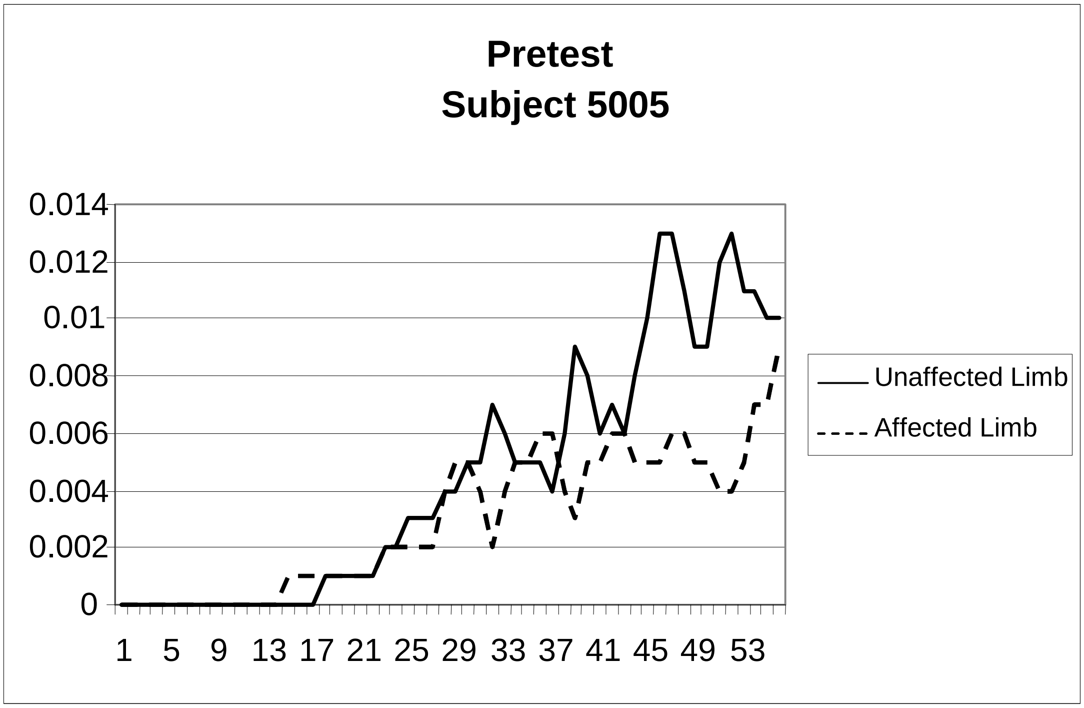

Figure 4-3. Power spectrum. Frequency (Hz) on x-axis. Power (μV2) on y-axis.

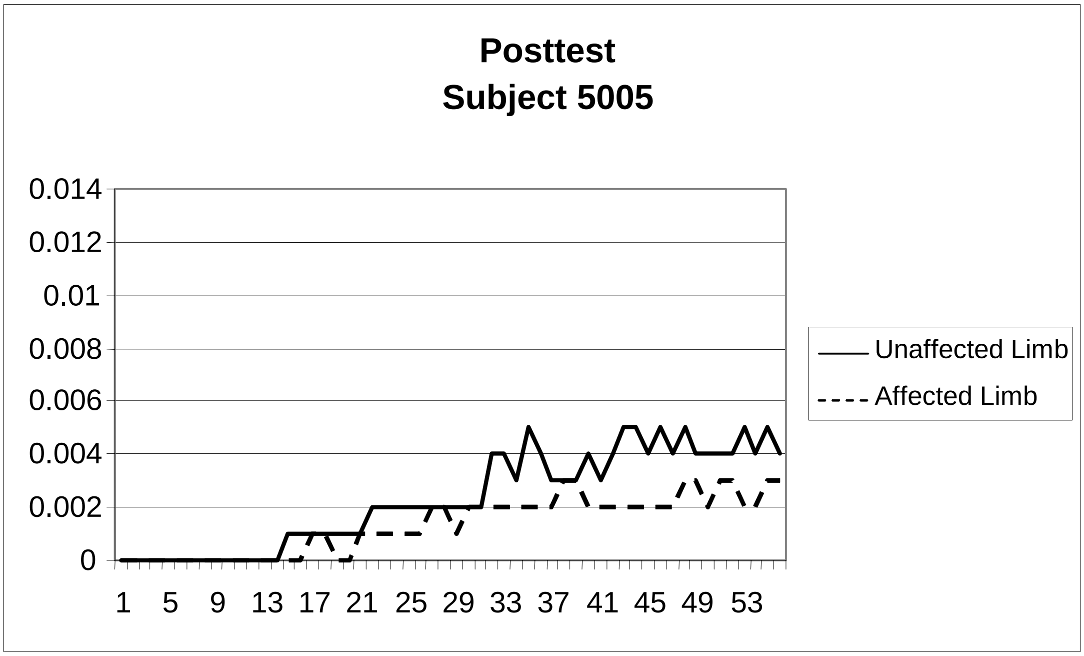

Figure 4-4. Power spectrum. Frequency (Hz) on x-axis. Power (μV2) on y-axis.

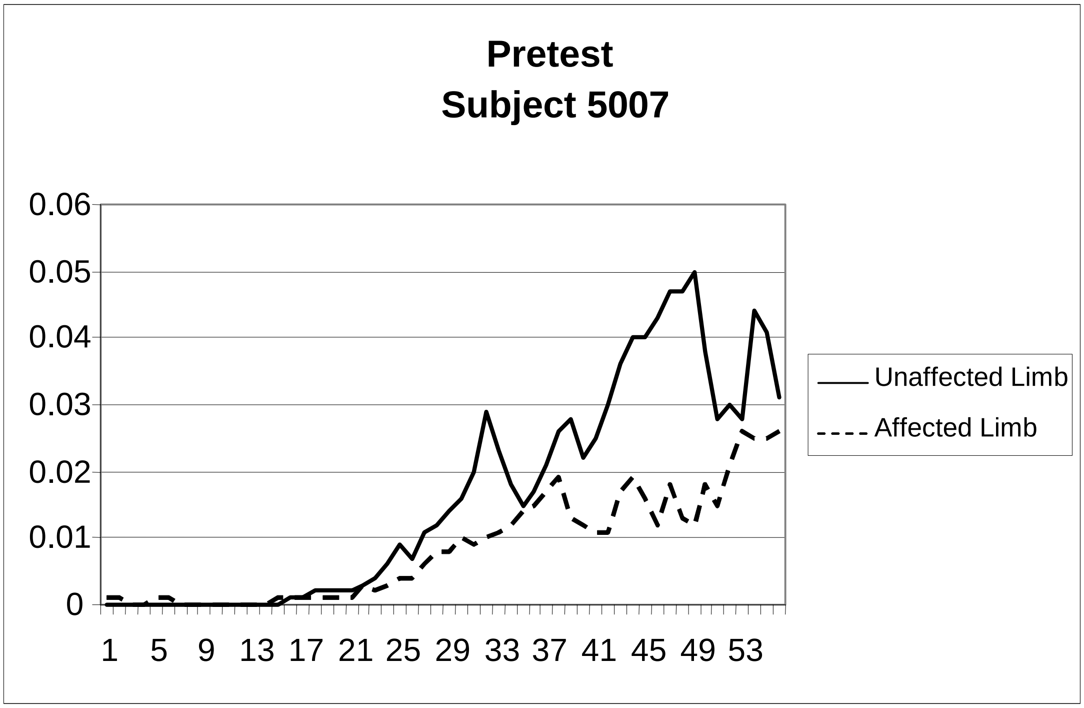

Figure 4-5. Power spectrum. Frequency (Hz) on x-axis. Power (μV^2) on y-axis.

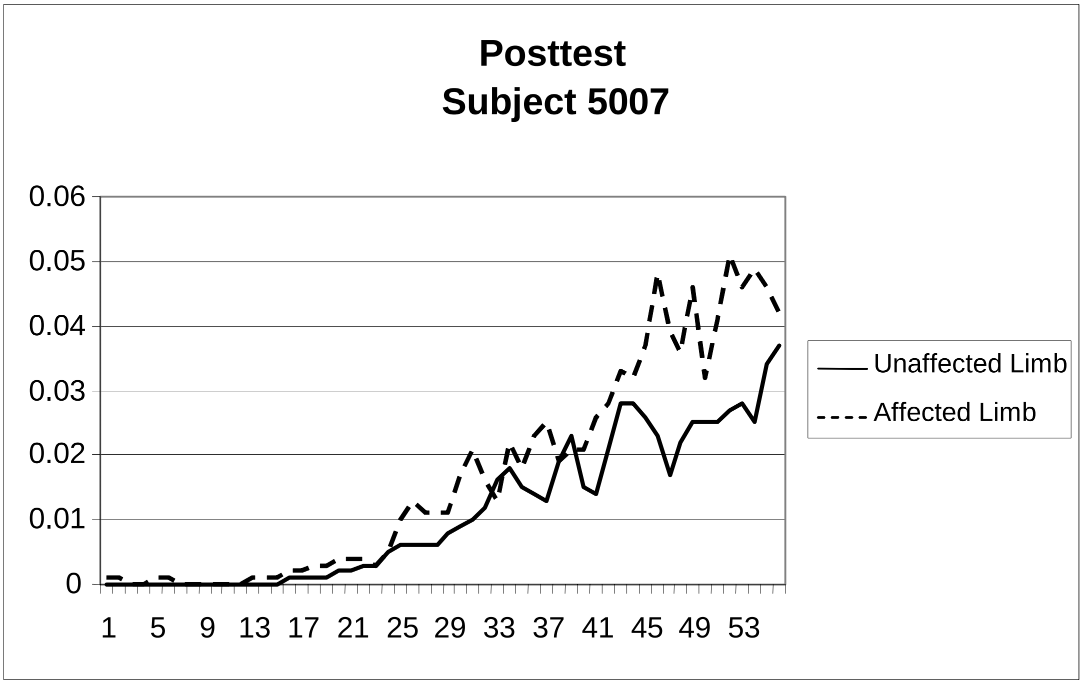

Figure 4-6. Power spectrum. Frequency (Hz) on x-axis. Power (μV^2) on y-axis.

Efficiency is the conservation of effort to accomplish a given task goal involving an interaction with the environment and more specifically, a ratio of the effective work output and the energy input into any system (Hatfield & Hillman, 2001). Kraemer (1994) expounded on this idea of efficiency using a muscle endurance training example, stating that the level of motor unit activation needed to maintain a given submaximal force decreases as the skill is acquired. Additionally, Kraemer argued that improved endurance performance may result in neural activity changes and lead to more efficient performance with lower energy expenditure. In the field of motor unit recruitment, DeVries and Housh (1994) used EMG measurements to show a gradual decrease in motor unit recruitment as a result of resistance training. Even the simplest central nervous system involves many neuromuscular events overlapping in time. Kelso, Tuller, and Harris (1983) suggested a need for an organizing principle to direct the proper timing and activation of several sets of muscles for a coordinated action to occur. The precise facilitation and inhibition that must take place in a coordinated movement is not simply several actions at one joint, but a synergy of muscles and joints constrained to act as a single unit. In other words, a complex action with many degrees of freedom is simplified to a more efficient model by the central nervous system. According to an extension of the general adaptation syndrome (GAS) proposed by Hans Selye (1976), when an organism is initially confronted with a specific task, it generally responds in an inefficient manner by firing both relevant and irrelevant neural pathways. As skill level increases, the neural networks are able to suppress irrelevant pathways and coordinate a skillful movement. This learning process is termed “pruning”, described as clipping away ineffective pathways and clearly activating effective neural pathways which lead to successful movements (Bell & Fox, 1996).

In the present pilot data, the average power decreases in the bimanual condition which indicates that the system is not recruiting larger motor units to create more force. Further, the system does not appear to be firing these motor units at a faster rate because the MPF does not increase in the bimanual condition. Therefore, one interpretation is that in the bimanual condition, the system is able to recruit more motor neurons of the same size and fire at the same frequency as in the unimanual condition to create greater force. In this method, smaller motor units are utilized to their fullest potential in an effort to preserve energy because they are fatigue-resistant. Based on this analysis, it can be concluded that after bimanual coordination training coupled with neuromuscular stimulation, stroke subjects perform more efficiently by producing a greater amount of force with less effort in a bimanual performance condition.

Overall, following a bimanual coordination protocol coupled with neuromuscular stimulation, stroke subjects are able to produce greater force in both unimanual and bimanual conditions. In addition, the system is more efficient when performing bimanually as is evidenced by the decreased average power in the bimanual condition.

Although stroke subjects appear to respond uniquely to the training administered, each group showed progress in the functional task, exhibiting a practical improvement. The coupled training protocol group showed improved performance in the Box and Block Test by increasing the average number of blocks moved by 8. Whereas, the weighted protocol group improved its average number of blocks moved by 3. In addition, though not statistically significant, there was an average increase when collapsing across subjects in power bands 3 and 4, as well as MPF and force. These averages are shown in Table 4-1.

Table 4-1. Averages collapsed across subjects and groups.

Dependent Measure	**Average Pretest**	**Average Posttest**	**Average Increase**
Power Band 3 (μV^2)	0.00135715	0.00190377	+0.00054662
Power Band 4 (μV^2)	0.00350579	0.00456317	+0.00105738
Mean Peak Frequency (Hz)	37.93329836	38.02371529	+0.09041693
Force (kg)	4.76181822	4.78578040	+0.02396218

Each subject exhibited improvement in at least one category, number of blocks moved, increased mean peak frequency, a change in power in the 30-55 Hz bands, or amount of force produced. However, no single uniform characteristic of motor improvement was shown by each stroke subject. Just as each stroke is unique and variable, so is each patient's rehabilitation and adaptation strategy. The short training period and less intense training schedule, may not yield physiological changes in the central nervous system or the muscles of the wrist and finger extensors as could be expected with a more strenuous schedule. Physiological adaptations poststroke because of a training regimen may only be evident through highly intensive therapy for a longer period of time which was not administered in the present studies (Oullette *et al.,* 2004). However, the improvements shown by each subject in the present protocol support the efficacy of both the weighted and coupled therapy. Whether range of motion, flexibility, strength, or a combination of these and other factors, is improved is unclear; however, the current findings indicate that the training is affecting the stroke subjects positively and this merits further research. In addition to discovering the type of training best suited for individual stroke survivors, it is also important to utilize spectral analysis as a noninvasive method of investigating motor unit recruitment. Although it is imperative to develop uniform subject groups when employing spectral analysis to eliminate strong variations which hide significant changes in the motor unit recruitment pattern of individuals, the analysis technique lends itself well to human trials because it uses surface EMG recordings. The use of spectral analysis to evaluate stroke motor recovery is important because is investigates recovery not a functional level, but at a physiological level. Employing spectral analysis in the investigation of motor unit recruitment changes in the stroke population is an important research avenue deserving of future attention.

APPENDIX
PILOT DATA

Two subjects from a bimanual coordination training protocol were used as pilot data. The data are presented for subjects 1102 and 2102 in both the unimanual and bimanual conditions for pre- and post-tests. In the unimanual and bimanual conditions, both subjects show an increase in average power in the beta and low gamma bands, increased mean peak frequency, and increased force production in the paretic limb.

Increased average power is indicative of a larger reliance on Type II muscle fibers, and thus an ability to recruit larger motor units (Bilodeau *et al.,* 1995). Therefore, it can be concluded that after participation in the bimanual training protocol, stroke subjects improve their ability to capitalize on Henneman's size principle to produce larger force values. That is, they were able to recruit larger motor units that are capable of greater force output. This is a critical finding which demonstrates the effectiveness of the training protocol. The increased average power is displayed in the beta and low gamma frequency bands which are controlled by the motor cortex. Therefore, a logical conclusion is that bimanual coordination exercises coupled with neuromuscular stimulation activates and strengthens the motor cortex. Figures A-1, A-2, A-3, A-4 display the increased average power in the beta and low gamma bands for subjects 1102 and 2102 pre and posttraining in the unimanual and bimanual conditions.

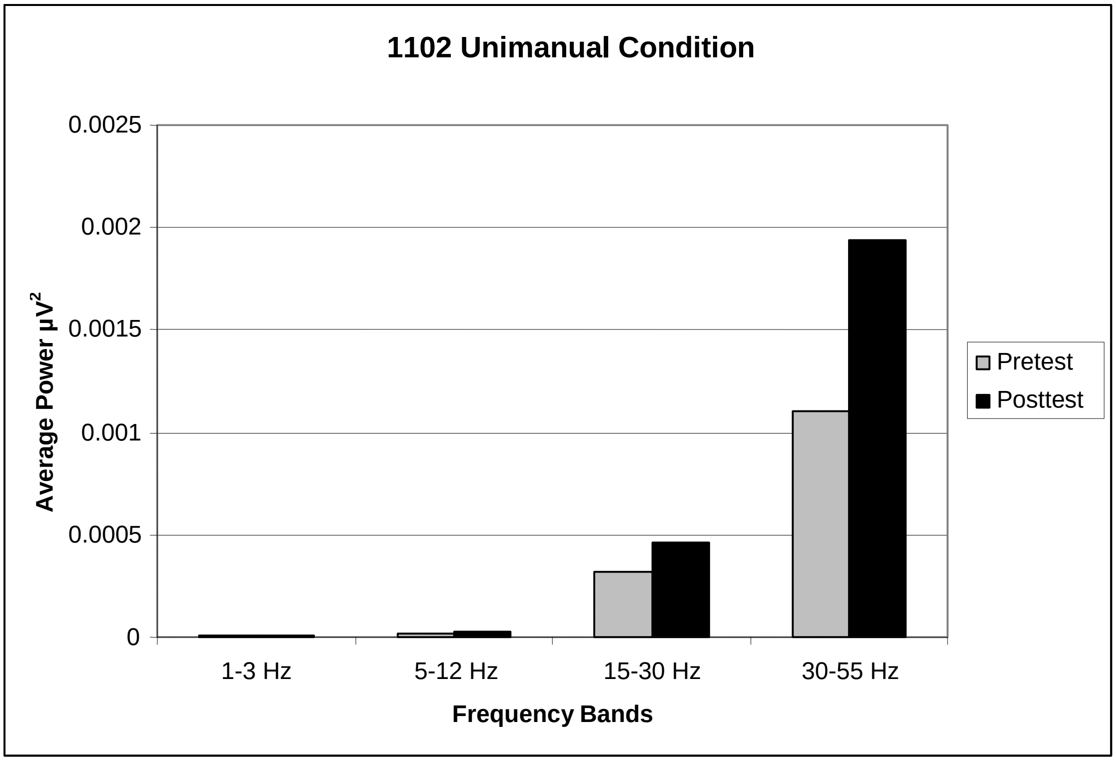

Figure A-1. Average power (subject 1102) in pre and posttests in unimanual condition.

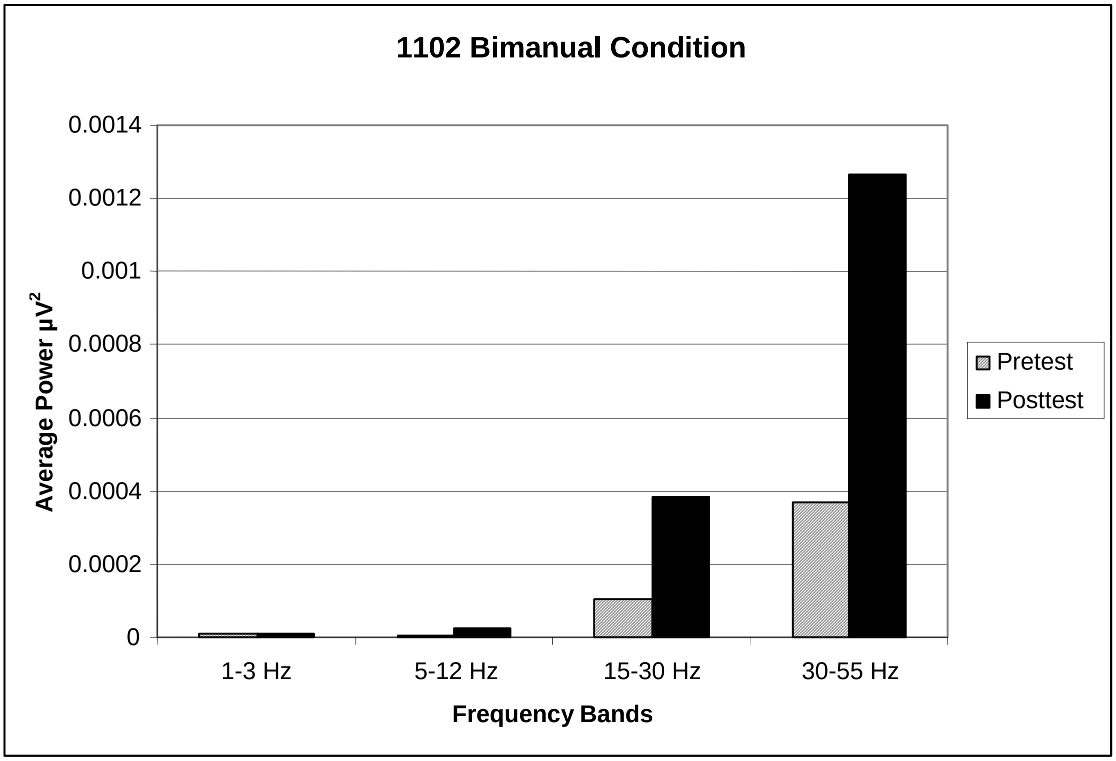

Figure A-2. Average power (subject 1102) in pre and posttests in bimanual condition.

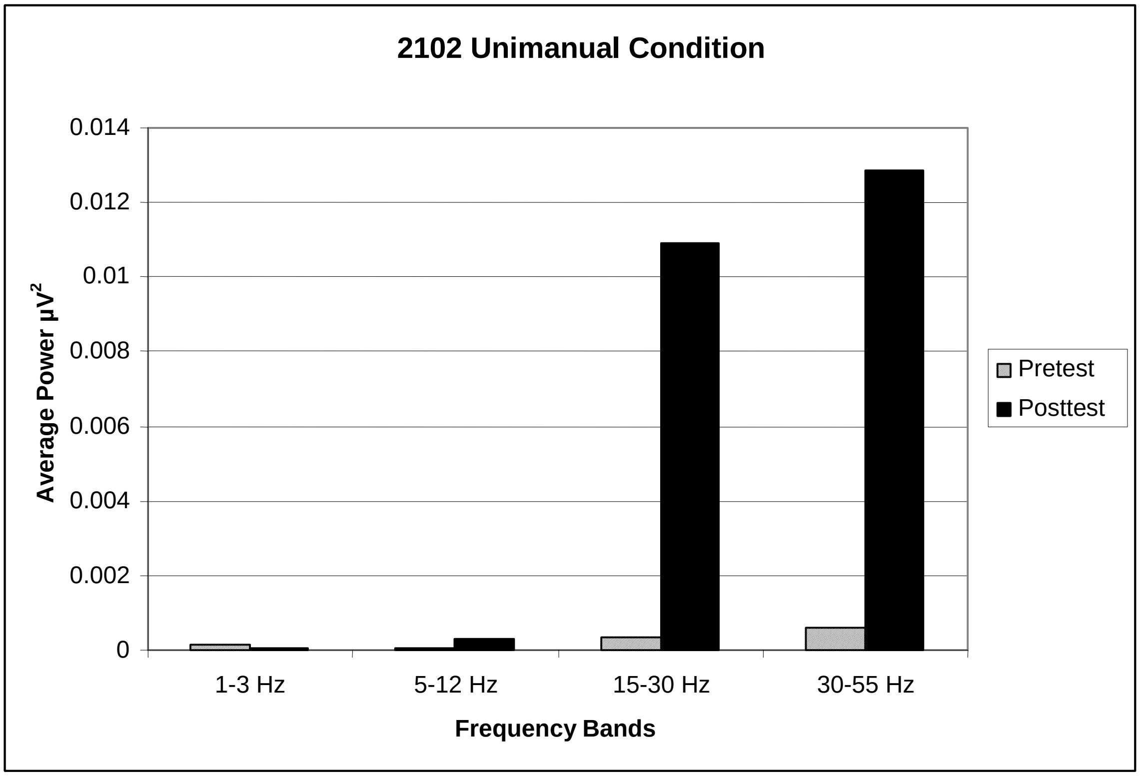

Figure A-3. Average power (subject 2102) in pre and posttests in unimanual condition.

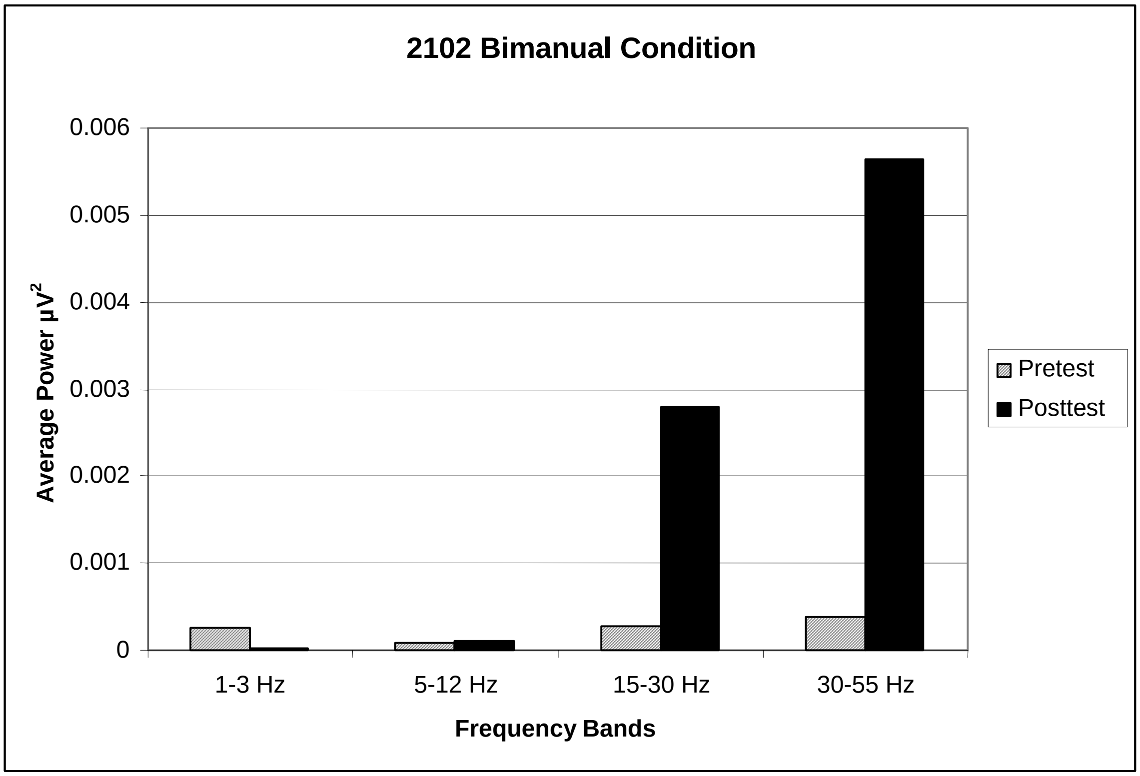

Figure A-4. Average power (subject 2102) in pre and posttests in bimanual condition.

Mean peak frequency (MPF) is indicative of the firing rate of individual motor units (Bilodeau *et al.,* 1995). Posttests reveal increased MPF for both subjects (see Figures A-5, A-6, A-7, A-8). An increase in MPF also indicates more of a reliance on Type II muscle fibers, just as increased average power shows. Hence, the same conclusions can be deduced. After training, stroke subjects are not only using larger motor units but also firing at higher frequencies which are the underlying mechanisms of the increased force production.

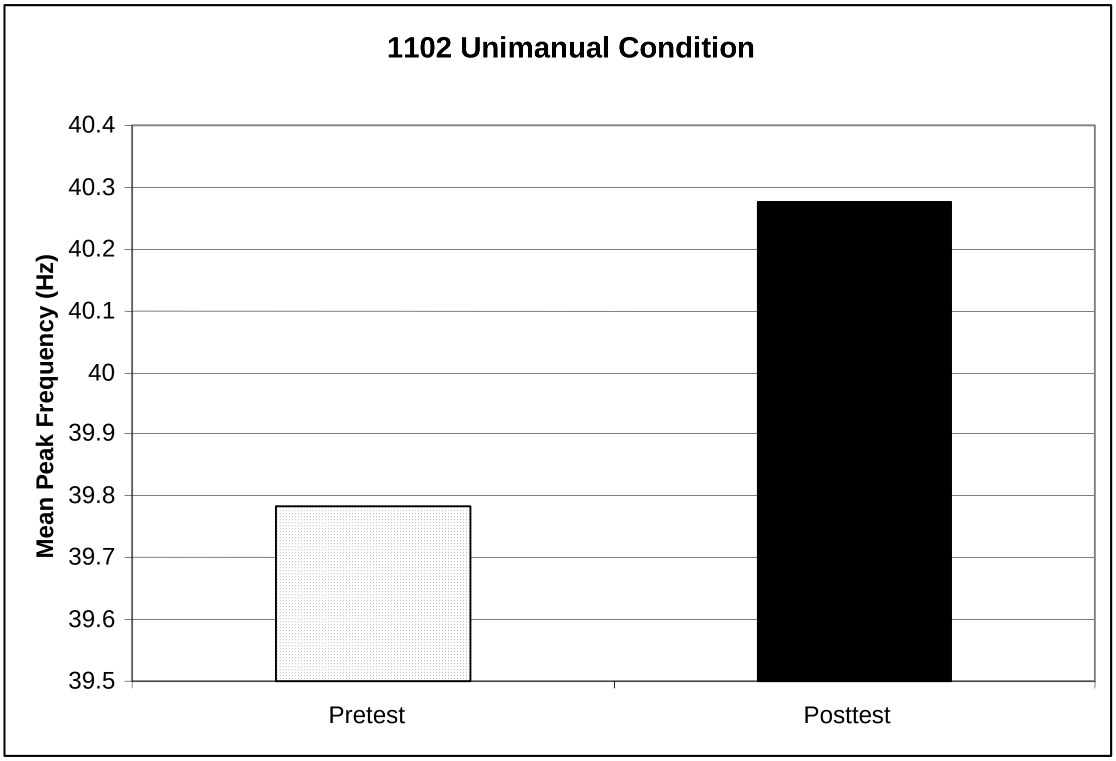

Figure A-5. Mean peak frequency (MPF) for subject 1102 in pre and posttests in unimanual condition.

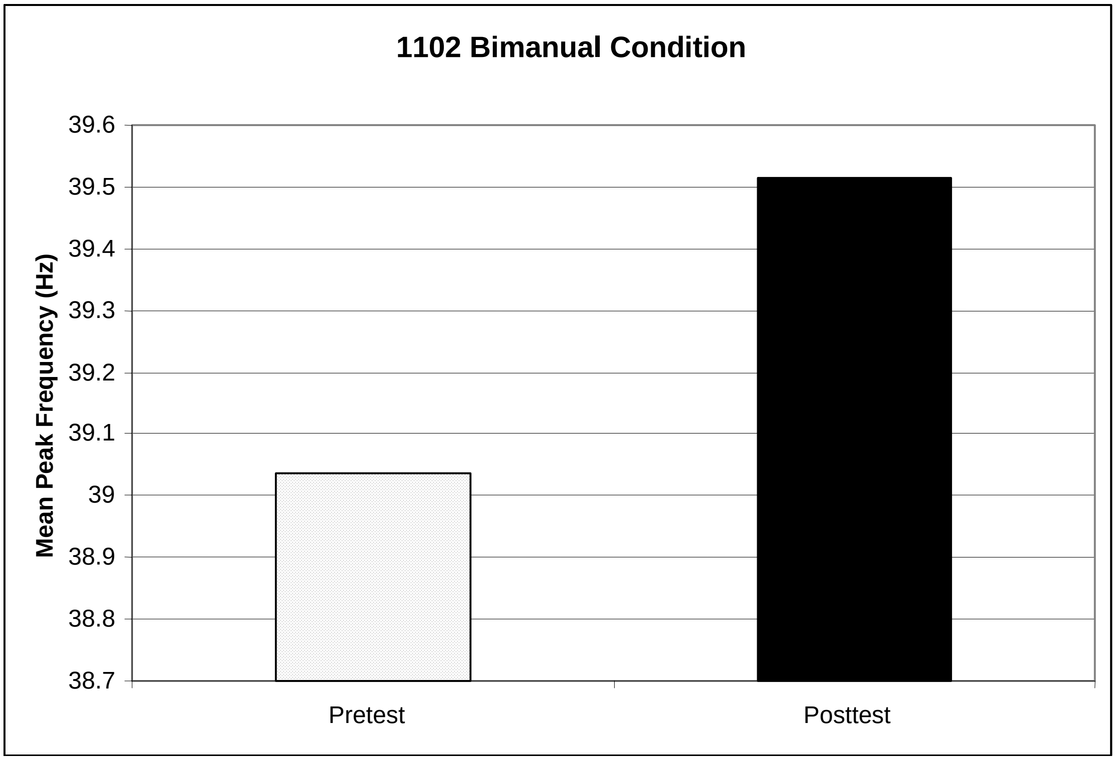

Figure A-6. Mean peak frequency (MPF) for subject 1102 pre and posttests in bimanual condition.

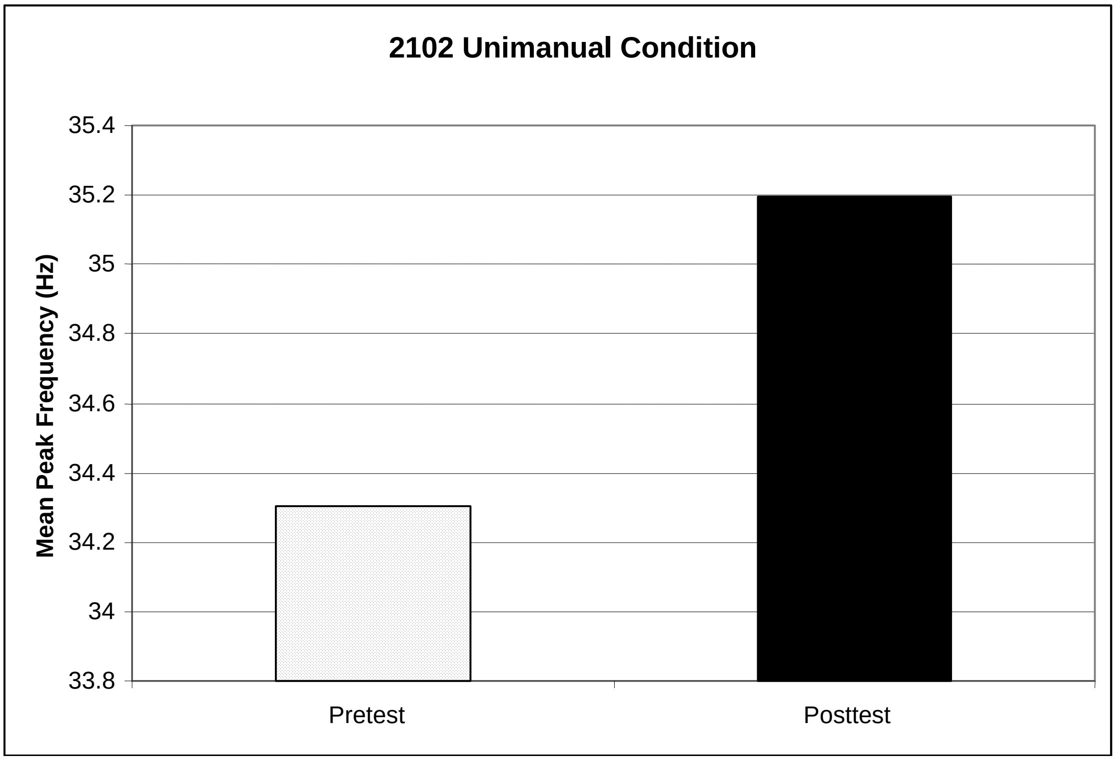

Figure A-7. Mean peak frequency (MPF) for subject 2102 pre and posttests in unimanual condition.

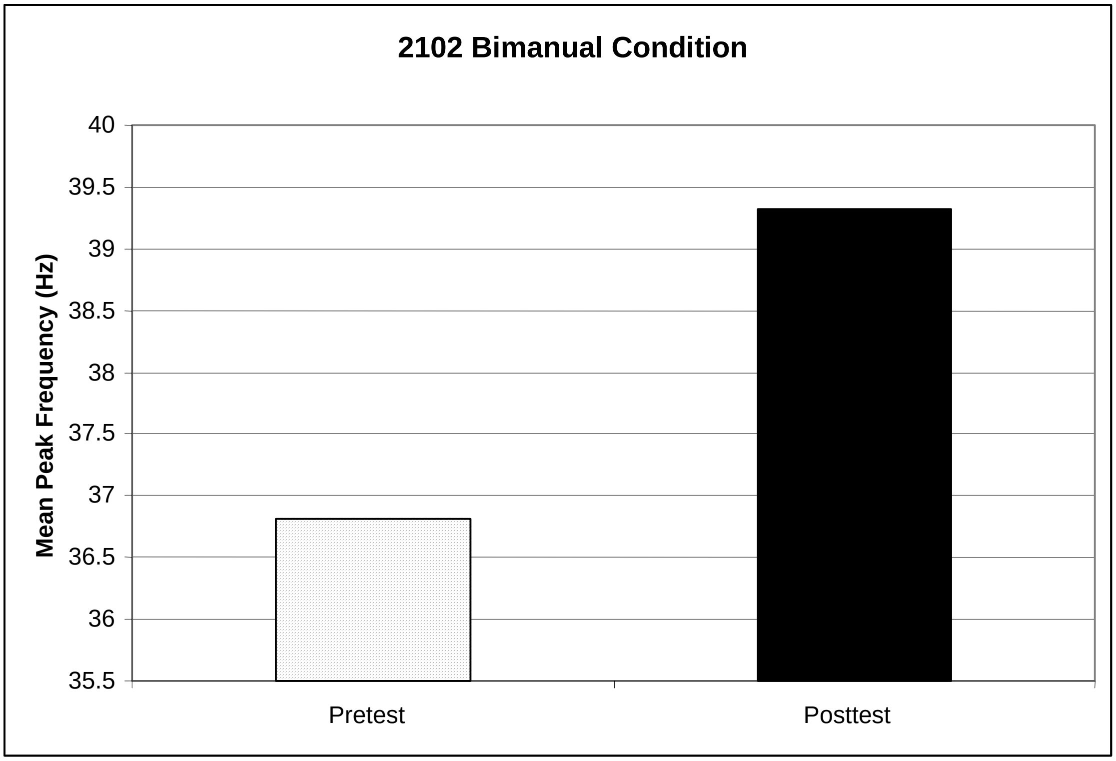

Figure A-8. Mean peak frequency (MPF) for subject 2102 pre and posttests in bimanual condition.

Research has demonstrated that in both the unimanual and bimanual conditions, stroke subjects exhibit increased average power in the beta and low gamma bands, increased mean peak frequency, and increased force production, all as expected. When comparing the post-tests of the unimanual and bimanual conditions, a decrease in power coupled with an increase in force production is observed (Figures A-9 and A-10). MPF in these conditions stays essentially equal and therefore will not be considered a factor for increasing the force in the bimanual condition. The justification for an increase in force accompanied by a decrease in average power of the beta and low gamma bands can be explained through a model of efficiency.

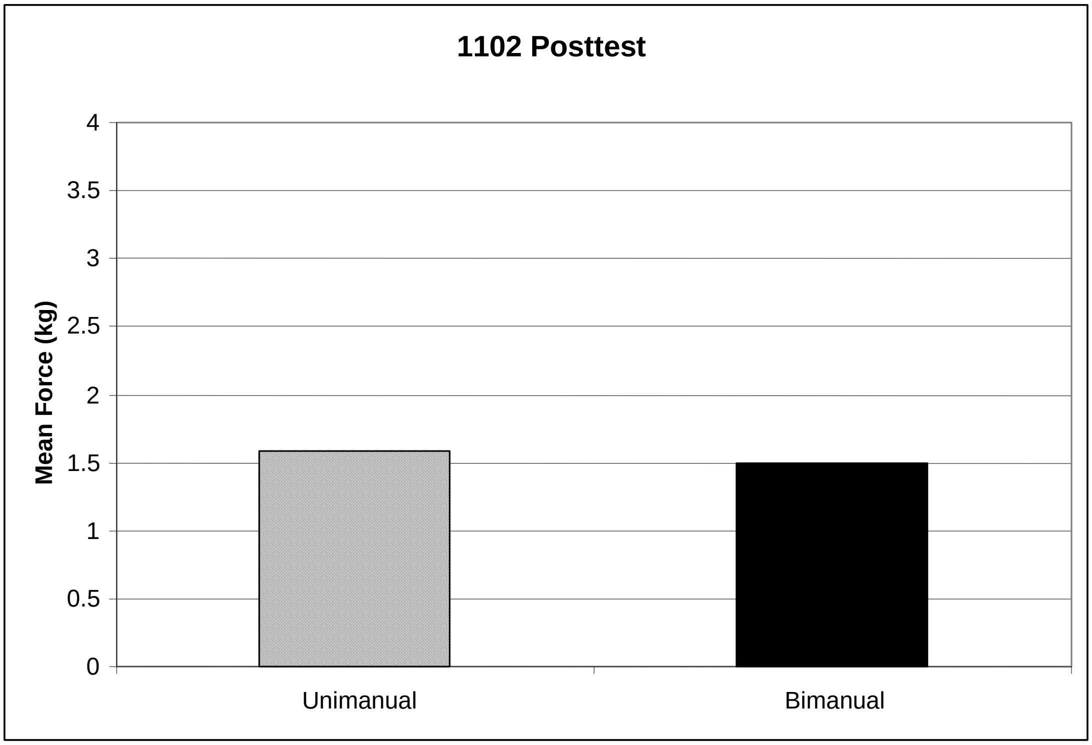

Figure A-9. Mean force (subject 1102) in posttests in the unimanual vs. bimanual conditions.

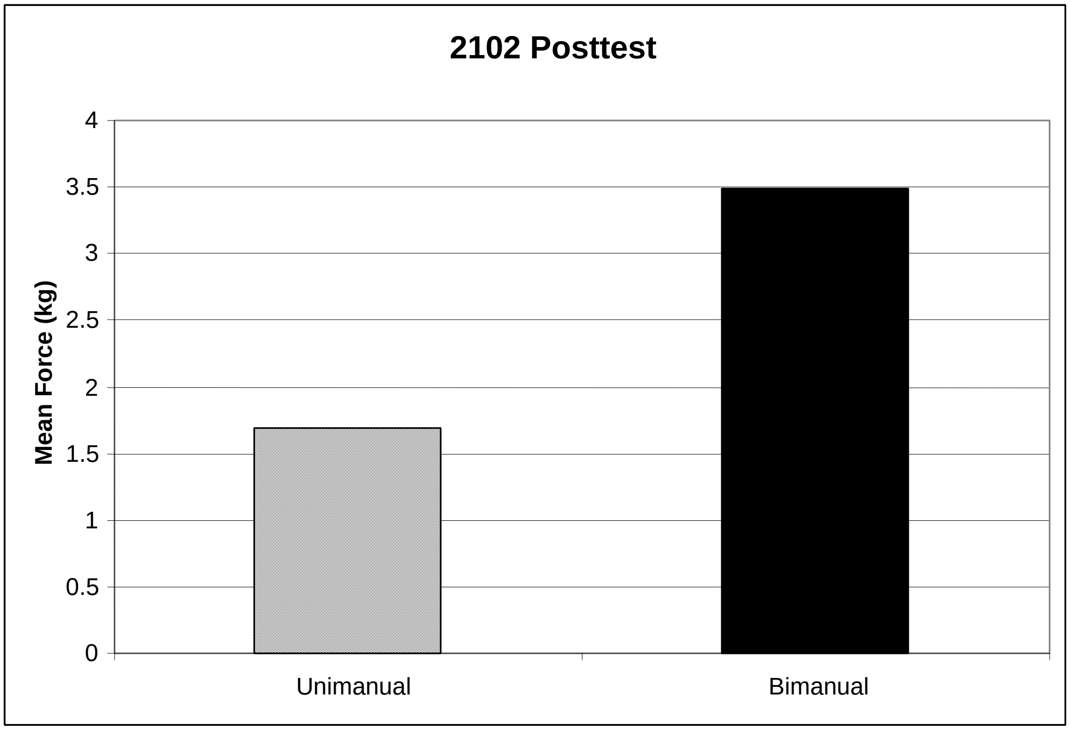

Figure A-10. Mean force (subject 2102) posttests in the unimanual vs. bimanual conditions.

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BIOGRAPHICAL SKETCH

Lindsay McManus was born in North Carolina in 1982. She graduated with honors from North Carolina State University with a Bachelor of Science degree in biomedical engineering and biological engineering. During a summer internship in Cincinnati, Lindsay joined a research team studying stroke and spinal cord injury recovery, which eventually led her to the University of Florida in 2004. Lindsay has worked with Dr. James Cauraugh in the Motor Behavior Laboratory investigating chronic stroke recovery through bilateral training and EMG-neuromuscular stimulation. While at the University of Florida, Lindsay also worked in the Biomechanics Laboratory with Dr. John Chow and Dr. Mark Tillman. In addition, she was also an instructor for the undergraduate motor learning/control course for four semesters. After graduating with a Master of Science degree in August 2006, Lindsay plans to enter the field of medical devices and implants.